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# Late Quaternary ice flow in a West Greenland fjord and cross-shelf trough system: submarine landforms from Rink Isbrae to Uummannaq shelf and slope

J.A. Dowdeswell [a,*], K.A. Hogan [a], C. Ó Cofaigh [b], E.M.G. Fugelli [c], J. Evans [d], R. Noormets [e]

[a] Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK
[b] Department of Geography, Durham University, Durham DH1 3LE, UK
[c] BP Norway, Godesetdalen 8, Postboks 197, 4065 Stavanger, Norway
[d] Department of Geography, Loughborough University, Loughborough LE11 3TU, UK
[e] The University Centre in Svalbard (UNIS), Postboks 156, 9171 Longyearbyen, Norway

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Sea-floor landforms and acoustic-stratigraphic records allow interpretation of the past form and flow of a westward-draining ice stream of the Greenland Ice Sheet, Rink Isbrae. The Late Pliocene–Pleistocene glacial package is several hundred metres thick and down-laps onto an upper Miocene horizon. Several acoustic facies are mapped from sub-bottom profiler records of the 400 km-long Uummannaq fjord-shelf-slope system. An acoustically stratified facies covers much of the fjord and trough floor, interpreted as glacimarine sediment from rain-out of fine-grained debris in turbid meltwater. Beneath this facies is a semi-transparent deformation-till unit, which includes buried streamlined landforms. Landform distribution in the Uummannaq system is used to reconstruct past ice extent and flow directions. The presence of streamlined landforms (mega-scale glacial lineations, drumlins, crag-and-tails) shows that an ice stream advanced through the fjord system to fill Uummannaq Trough, reaching the shelf edge at the Last Glacial Maximum. Beyond the trough there is a major fan built mainly of glacigenic debris flows. Turbidity-current channels were not observed on Uummannaq Fan, contrasting with well-developed channels on Disko Fan, 300 km to the south. Ice retreat had begun by 14.8 cal. ka ago. Grounding-zone wedges (GZW) in Uummannaq Trough imply that retreat was episodic, punctuated by several still-stands. Ice retreat between GZWs may have been relatively rapid. There is little sedimentary evidence for still-stands in the inner fjords, except for a major moraine ridge marking a Little Ice Age maximum position. On the shallow banks either side of Uummannaq Trough, iceberg ploughing has reworked any morphological evidence of earlier ice-sheet activity.


## 1. Introduction

Today, the outlet glaciers draining huge interior basins of the Greenland Ice Sheet are among the fastest-flowing on Earth (Rignot and Kanagaratnam, 2006). Their changing dynamics are likely to be a critical control on the rate of sea-level rise during the 21st Century (Rignot and Kanagaratnam, 2006; Pfeffer et al., 2009; Shepherd et al., 2012). Equally, the Greenland Ice Sheet is known to have expanded during the Last Glacial Maximum (LGM), about 20,000 years ago, providing an important increment of global sea-level fall at that time (e.g. Clark and Mix, 2002). Investigations of terrestrial glacial and related deposits have demonstrated clearly that ice expanded through the main fjord systems of Greenland to reach at least the outer coast at the last full-glacial (e.g. Funder and Hansen, 1996; Funder et al., 2011; Roberts et al., 2013). This view is supported by numerical modelling of rebound from past ice-sheet loading which utilises observations of dated raised beaches around the coast and offshore islands of Greenland (e.g. Fleming and Lambeck, 2004). It is less clear, however, both where and how far the ice sheet may have advanced across the wide continental shelf surrounding Greenland, and what the nature of full-glacial and deglacial ice dynamics may have been. Recent marine-geophysical evidence from several parts of East Greenland implies advance to the outer shelf or shelf edge (e.g. Evans et al., 2002, 2009; Ó Cofaigh et al., 2004; Dowdeswell et al., 2010; Winkelmann et al., 2010). Marine evidence from the fjords and shelf of West

* Corresponding author.
*E-mail address:* jd16@cam.ac.uk (J.A. Dowdeswell).

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Greenland is relatively limited (e.g. Roksandic, 1979; Kuijpers et al., 2007; Hogan et al., 2011; Schumann et al., 2012); our 2009 cruise to the Disko and Uummannaq systems has yielded much new data on the extent, dynamics and timing of Late Quaternary ice-sheet behaviour (Hogan et al., 2012; Ó Cofaigh et al., 2013a). Ó Cofaigh et al. (2013a) focus, in particular, on radiocarbon-dated sediment cores and the timing of ice-sheet maximum extent and retreat.

In this paper, we present the full details of marine-geophysical observations of sea-floor landforms and sediments from the 250 km-wide continental shelf offshore of Uummannaq Fjord in West Greenland (70°30′ to 71°N), and in the 150 km-long fjord system that links the present ice sheet with the Uummannaq cross-shelf trough beyond (Fig. 1). Thus, our observations extend from within a kilometre of the present margin of Rink Isbrae, a major fast-flowing outlet of the Greenland Ice Sheet (Rignot and Kanagaratnam, 2006), to the shelf edge and continental slope in Baffin Bay; a transect of about 400 km. Swath-bathymetric data revealing sea-floor morphology, and accompanying acoustic-stratigraphic records, allow us to interpret the form and flow of a major outlet glacier of the ice sheet at, and following the Last Glacial Maximum (LGM), including both its past extent across the West Greenland shelf and its flow regime and style of deglaciation (e.g. Dowdeswell et al., 2008a).

## 2. Background: seismic stratigraphy and glacial history

The Uummannaq Fjord complex consists of eleven individual fjords draining into a single cross-shelf trough (Uummannaq Trough) that is about 50 km wide and extends across the adjacent continental shelf, opening into the deep waters of Baffin Bay (Fig. 1). Bathymetric data show that the deep inland fjords coalesce southeast of Ubekendt Ejland on the inner shelf to form the much larger Uummannaq Trough (Jakobsson et al., 2012) (Fig. 1). This trough is one of several large cross-shelf troughs that dissect the modern West Greenland continental shelf (Batchelor and Dowdeswell, 2013; Ó Cofaigh et al., 2013a); the troughs are probably related to repeated advance and retreat cycles of the Greenland Ice Sheet over the continental shelf during the Quaternary.

The Quaternary glacial history of the Uummannaq system, including that of the LGM, is not particularly well known. Two seismic-reflection profiles from the upper slope and shelf offshore of the Uummannaq fjord system, located in Fig. 1, provide the long-term stratigraphic context for our investigations of Late Quaternary ice flow across the West Greenland continental shelf between 70° and 71°N (Fig. 2). The upper profile is a dip line acquired along the axis of Uummannaq Trough (Fig. 2A), whereas the lower profile is a strike line across the trough in the outer part of the shelf (Fig. 2B). The Late Pliocene–Pleistocene glacial interval is several hundred metres thick and is made up of a number of distinctive units which down-lap onto an upper Miocene horizon. The Miocene–Pliocene sediments offshore dip westwards and reflect uplift and tilting of the West Greenland coast (Fig. 2). Uplift and erosion of adjacent landmasses is also supported by Miocene unconformities and an angular unconformity at the base of the onshore Plio-Pleistocene sediments (Henriksen, 2008). Time-equivalent uplift to the east

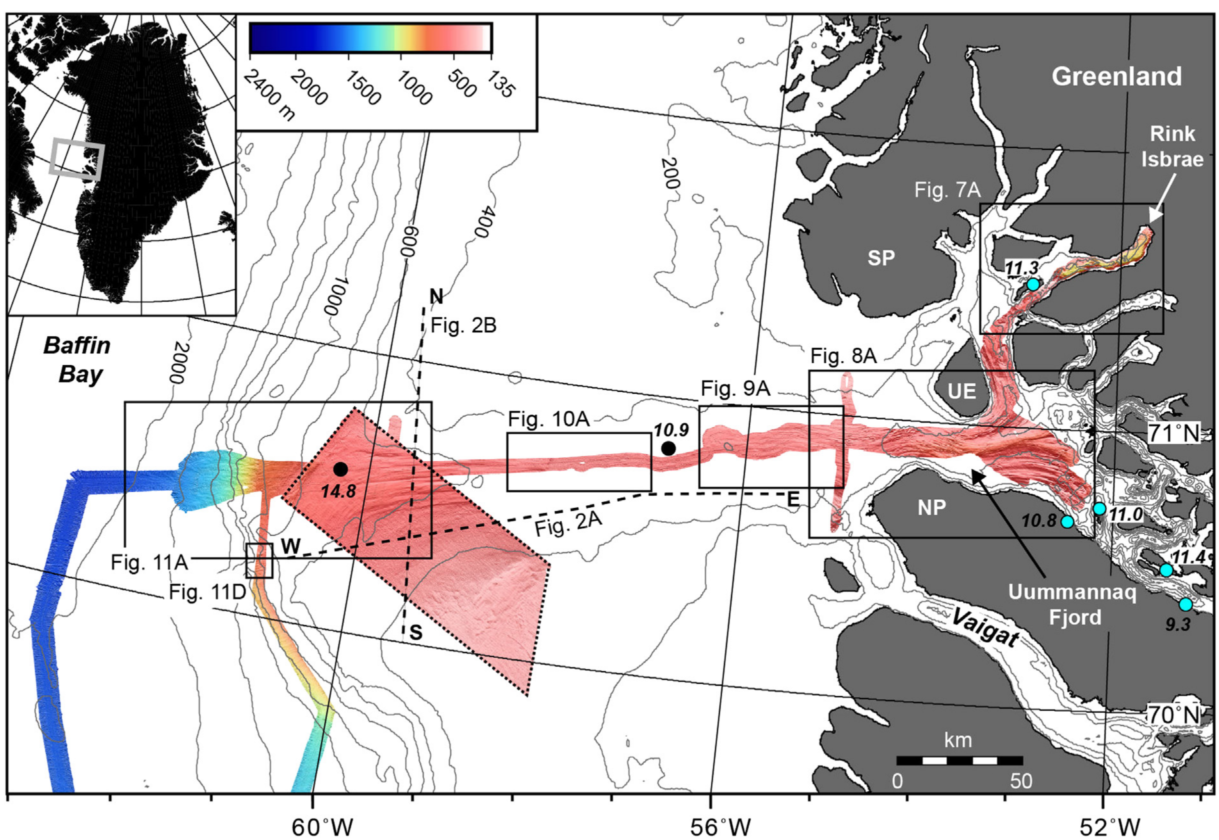


**Fig. 1.** Map of the central West Greenland continental margin between 69° and 72°N showing the area covered by swath-bathymetric data (colour shaded). Bathymetric contours are at 200 m intervals. Minimum dates for deglaciation for Uummannaq Trough are shown as black circles (marine $^{14}C$ dates in cal. ka) and blue circles (terrestrial cosmogenic radionuclide exposure dates in ka); dates from Ó Cofaigh et al. (2013a,b), Roberts et al. (2013) and McCarthy (2011). UE is Ubekendt Ejland, NP is Nuussuaq Peninsula, SP is Svartenhuk Peninsula. The locations of subsequent figures are shown. The position of the study area within Baffin Bay and Greenland is inset. The large rectangular block of swath-bathymetric data on the outer shelf (dotted outline) is reproduced courtesy of Cairn Energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

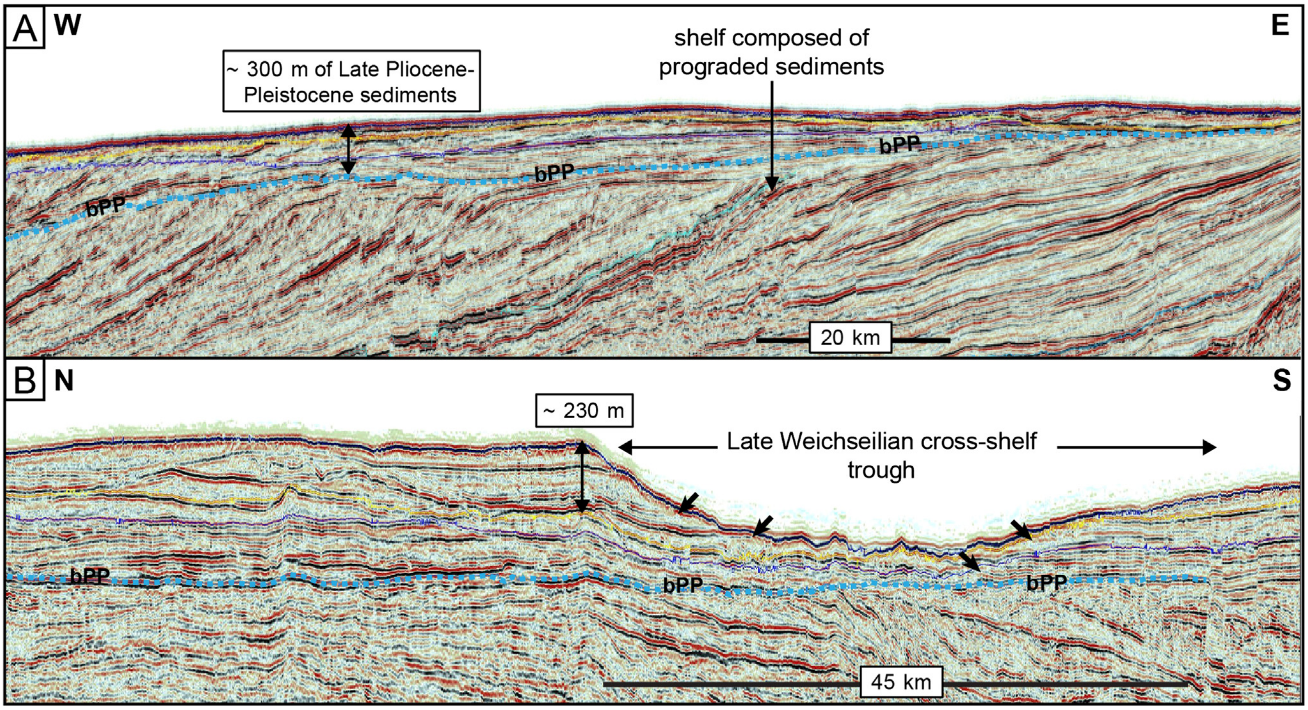


**Fig. 2.** Seismic-reflection profiles on the outer Uummannaq shelf (located in Fig. 1). (A) 130 km-long dip line showing westward shelf progradation. (B) 110 km-long strike line, showing a Late Quaternary trough where glacial erosion has truncated pre-existing reflections (black arrows). In the absence of well control, the seismic data were phase-rotated to yield a positive amplitude zero-phase wavelet at the seabed, with increases in impedance producing a positive seismic amplitude. The reflection marked bPP in each of the panels represents the lower boundary of Plio-Pleistocene erosion and glacier-influenced sediments.

triggered erosion by westward-flowing rivers and glaciers, forming the source of the thick Pliocene and Quaternary prograding sedimentary fans observed on the West Greenland Shelf.

The glacial deposits form a thick succession of prograding wedges (Fig. 2A). The dipping reflections in the seismic line along the axis of Uummannaq Trough imply that loading of the shelf by sediment delivery during successive Quaternary ice advances has provided accommodation space to enable continuing shelf progradation (Fig. 2A) (Dowdeswell et al., 2007); the shelf has prograded seaward at least 200 km (Fig. 2A). However, the most recent glacial advances appear to have resulted in aggradation rather than progradation of the shelf. The upper parts of the dipping reflections are often cut by erosion related to subsequent glacial advances across the shelf. Erosion of underlying reflections is well illustrated in the outer-shelf strike line, where the truncation of several seismic reflections by ice stream erosion can be seen at the sides of the Late Weichselian trough (Fig. 2B). Plio-Pleistocene chronological control is difficult due to a lack of seismic calibration points in the area.

Concerning the Late Weichselian, a recent review of Late Quaternary data by Funder et al. (2011) placed a “conceptual” LGM ice-sheet margin on the inner shelf just offshore the Nuussuaq Peninsula and Ubekendt Ejland. Funder et al. (2011) acknowledged, however, that this could be a minimum ice-sheet limit and did not preclude ice extending to the shelf break or outlet glaciers crossing the continental shelf in bathymetric troughs. This conservative inner shelf ice-sheet limit is based on the presence of low weathering limits and undisturbed pre-Weichselian marine sediments on the nearby Svartenhuk Peninsula that Kelly (1985) suggested was evidence for LGM ice remaining on land just north of the Uummannaq fjord system.

More recently, marine geophysical and geological data acquired from the outer shelf and slope region of Uummannaq Trough now provide evidence for a grounded, fast-flowing outlet glacier reaching the shelf edge and delivering sediment to a prominent trough-mouth fan during the LGM (Ó Cofaigh et al., 2013a,b). This much more extensive glaciation of Uummannaq Trough may seem contradictory when compared with ice-free coastal areas on the Svartenhuk Peninsula (Kelly, 1985), but could be explained by the strong southerly routing of the inland ice flux into Uummannaq Trough east of Ubekendt Ejland (Roberts et al., 2013).

The pattern and timing of deglaciation after the LGM also remain uncertain for much of the Greenland Ice Sheet. New radiocarbon dates from the central West Greenland continental shelf, located in Fig. 1, indicate that deglaciation from the shelf edge was underway in Uummannaq Trough by 14.8 cal. ka ago but occurred somewhat later (13.8–12.2 cal. ka ago) in Disko Trough about 250 km to the south (Ó Cofaigh et al., 2013a). Following initial retreat, the outlet glacier in Disko Trough is thought to have readvanced onto the outer shelf during the Younger Dryas chron (Ó Cofaigh et al., 2013a). Less is known about the behaviour of ice in Uummannaq Trough at this time; however, ice had retreated from the middle continental shelf in Uummannaq Trough (some 80 km offshore of Ubekendt Ejland; Fig. 1) by 10.9 cal ka ago (McCarthy, 2011). This indicates that grounded ice remained on the middle to outer shelf in this trough during the Younger Dryas cold period (Jennings et al., 2013; Roberts et al., 2013). Cosmogenic radiogenic nuclide dates from glacially-scoured bedrock surfaces and terrestrial radiocarbon dates east of Ubekendt Ejland range from 11.4 to 10.7 cal. ka ago (Fig. 1). The dates imply rapid retreat by iceberg calving through innermost Uummannaq Fjord at this time (Bennike and Bjork, 2002; Roberts et al., 2013). Recession into the Uummannaq fjord complex was early compared with retreat in Disko Bay, where ice only reached a position at the mouth of Jakobshavn Isfjord by about 10 cal. ka ago (Weidick, 1968; Long et al., 2006; Weidick and Bennike, 2007). After this, in the Uummannaq area,

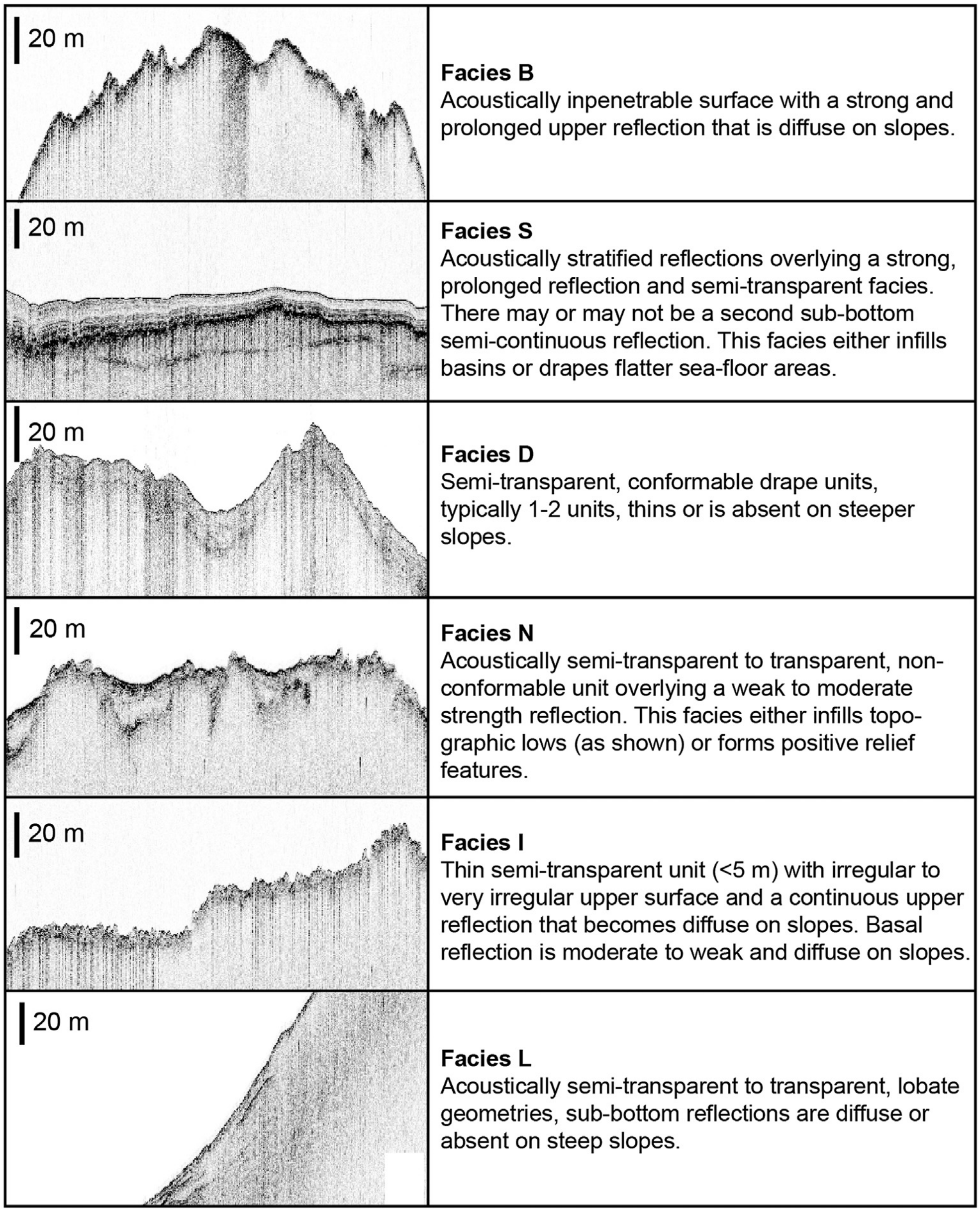


**Fig. 3.** Image and description of each of the six acoustic facies observed on TOPAS shallow sub-bottom profiles in the Uummannaq fjord, shelf, slope system.

ice may have stabilised somewhere close to fjord mouths, possibly at topographic pinning points, during the early Holocene before retreating eastward behind this limit sometime before 9.3 cal. ka ago (Roberts et al., 2013).

## 3. Methods

The geophysical datasets used in this study were acquired mainly from the RRS *James Clark Ross* (JCR) in September 2009 using hull-mounted Kongsberg Simrad multibeam swath-bathymetry and Topographic Parametric Sonar (TOPAS) sub-bottom profiler systems. The swath system was a deep-water 12 kHz EM-120 with 191 beams and a 1° by 1° beam configuration. Swath data covering an area of 7275 km$^2$ were processed through the removal of anomalous pings and gridded at cell sizes of 20–50 m using the MBSystem and Fledermaus softwares. Depth measurements have vertical and horizontal uncertainties of about 1 m and 5 m, respectively. The TOPAS parametric acoustic profiler has a secondary frequency of 0.5–5 kHz. Navigation data were acquired using differential GPS. The area over which geophysical data were acquired across the fjord-shelf-slope system of the Uummannaq area of the central West Greenland margin is shown by the swath-bathymetric data coverage in Fig. 1. In addition, Cairn Energy have undertaken swath-bathymetric mapping of a 3600 km$^2$ area on the outer Uummannaq shelf (Fig. 1).

## 4. Shallow acoustic facies in the Uummannaq system

### 4.1. Acoustic facies types

Six acoustic facies are identified and described from the Uummannaq fjord, shelf and slope system from TOPAS sub-bottom profiler records (Fig. 3); their spatial distribution is mapped in Fig. 4. TOPAS profiles were available for the whole of the area of swath-bathymetric coverage shown in Fig. 1, with the exception of the outer-shelf rectangle of data obtained from Cairn Energy. The systematic description and mapping of shallow acoustic facies is similar to the approach we have taken on a number of other Arctic shelves (e.g. Dowdeswell et al., 2010).

The first acoustic facies, Facies B, is represented by a strong and prolonged sea-floor reflection that becomes more diffuse on steeper slopes (Fig. 3). The sea floor appears impenetrable to the TOPAS system; this is typical of bedrock at the sea floor (e.g. Dowdeswell et al., 2010), although in some cases relatively strong reflections may also represent overconsolidated glacial till. Given the rough and uneven sea floor topography found in a number of areas of inner Uummannaq Fjord, it is likely that Facies B represents bedrock in most parts of the study area where it is present.

Facies S is characterised by acoustically stratified reflections (Fig. 3). This facies typically overlies a strong and prolonged reflector with a semi-transparent facies sometimes visible beneath it. Occasionally, a further, semi-continuous reflection is present beneath the semi-transparent unit. Facies S stratified sediments either drape the submarine topography or infill small depressions within the sea floor. This acoustically stratified facies is interpreted as glacimarine sediment probably derived predominantly from the rain-out of fine-grained suspended sediment that is delivered to the ice margin as turbid meltwater plumes; the rate of sedimentation by rain-out from turbid meltwater declines with distance from the sediment source at subglacial, ice-marginal and glacifluvial channels (e.g. Syvitski, 1989; Powell, 1990; Mugford and Dowdeswell, 2011). Facies S is also likely to contain some poorly sorted iceberg-rafted debris, given the large numbers of icebergs which are calved from the fast-flowing outlet glaciers, such as Rink Isbrae, that drain into the Uummannaq fjord system (Rignot and Kanagaratnam, 2006). In more ice-distal settings, the facies may become predominantly hemipelagic. The strong and prolonged reflector buried beneath the stratified facies is interpreted as the surface of a semi-transparent deformation till unit (Dowdeswell et al., 2004; Ó Cofaigh et al., 2005), which includes streamlined landforms that were produced at the base of past ice streams (e.g. Clark, 1993; Ó Cofaigh et al., 2003; Ottesen et al., 2005). These subglacially produced landforms are still recognisable in swath bathymetry of the region, as their morphological form is not masked by the overlying metres of acoustically stratified sediments (e.g. Fig. 6B).

Facies D is a semi-transparent, conformable unit that drapes the sea-floor topography (Fig. 3). It typically comprises one to two sub-units, although occasionally up to four, and is up to 15 m thick; it thins or is absent on very steep slopes. This facies appears to be the correlative of Facies S, but accumulates on steeper slopes where stratification is either not present or is not resolved on TOPAS records. Sediments of this facies are, therefore, interpreted as glacimarine to hemipelagic, derived from similar sources to those of Facies S, but forming on steeper slopes. Similarly to Facies S, there is evidence that megascale glacial lineations are buried beneath several metres of sediments of Facies D, especially in the inner shelf and outer fjord system (e.g. Fig. 6A).

Facies N is a semi-transparent to transparent but non-conformable acoustic facies (Fig. 3). It usually overlies a moderate to weak sub-bottom reflection. Sediments of Facies N appear to either infill basins or to form positive-relief features on the sea floor. This is probably a subglacial till unit which infills depressions in relatively rugged areas, and forms positive-relief mounds in some areas which also contain streamlined sedimentary landforms.

Facies I is a thin semi-transparent unit that is usually less than about 5 m in thickness (Fig. 3). It is characterised by an irregular to rough surface of a metre or two in amplitude. It is typically underlain by a moderate to weak basal reflection that tends to become more diffuse as slope angle increases. This acoustic facies is interpreted to have been relatively heavily affected by the ploughing action of iceberg keels, which accounts for the highly irregular upper surface (e.g. Dowdeswell et al., 1993, 2010). The unit itself is likely to be glacimarine sediment, somewhat similar to Facies D, reworked by iceberg keels and overlying what may often be an overconsolidated glacial till, or occasionally, bedrock.

Facies L is a semi-transparent to transparent acoustic facies that has a distinctive lobate geometry (Fig. 3). Sub-bottom reflections are sometimes diffuse or absent on steep slopes. This facies, which is found only on the upper continental slope, is similar to lobate features interpreted as debris-flow deposits that have been reported from many Arctic and Antarctic slope settings offshore of glacier-influenced cross-shelf troughs (e.g. Laberg and Vorren, 1995; Dowdeswell et al., 1996, 2008b; 2010).

### 4.2. Distribution of acoustic facies in the Uummannaq system

The geographical distribution of the six acoustic facies in the Uummannaq fjord-shelf-slope system has been mapped out and is shown in Fig. 4. There is a clear pattern to the occurrence of each

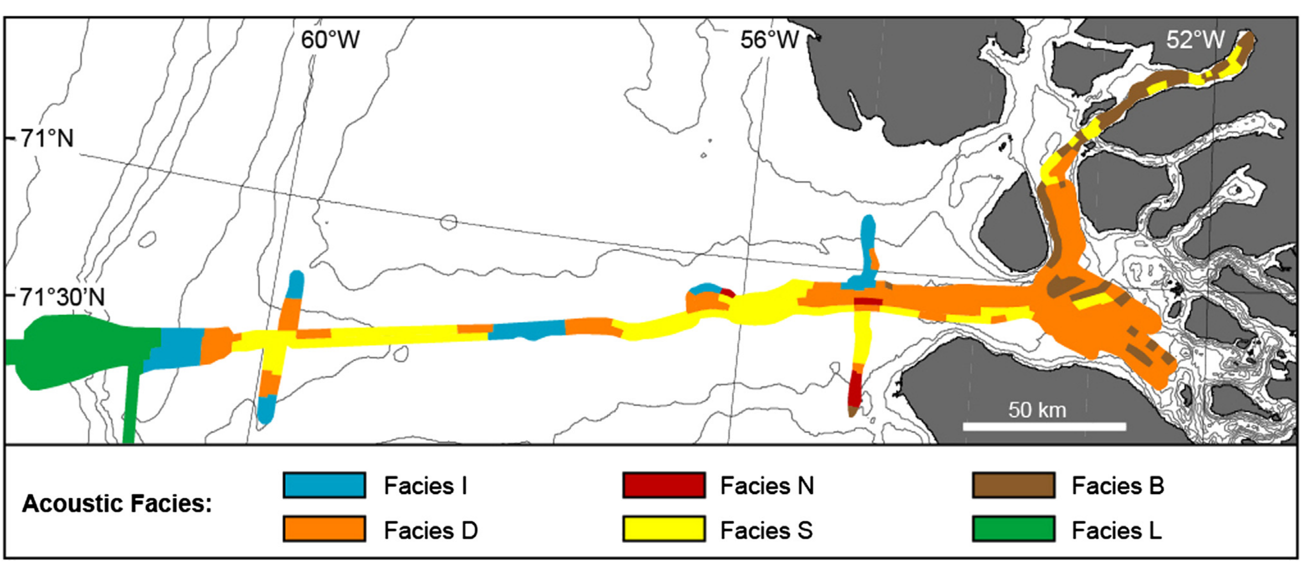


**Fig. 4.** Map of the distribution of the six acoustic facies observed in the 400 km-long study transect from Rink Isbrae to the continental slope offshore of Uummannaq shelf.

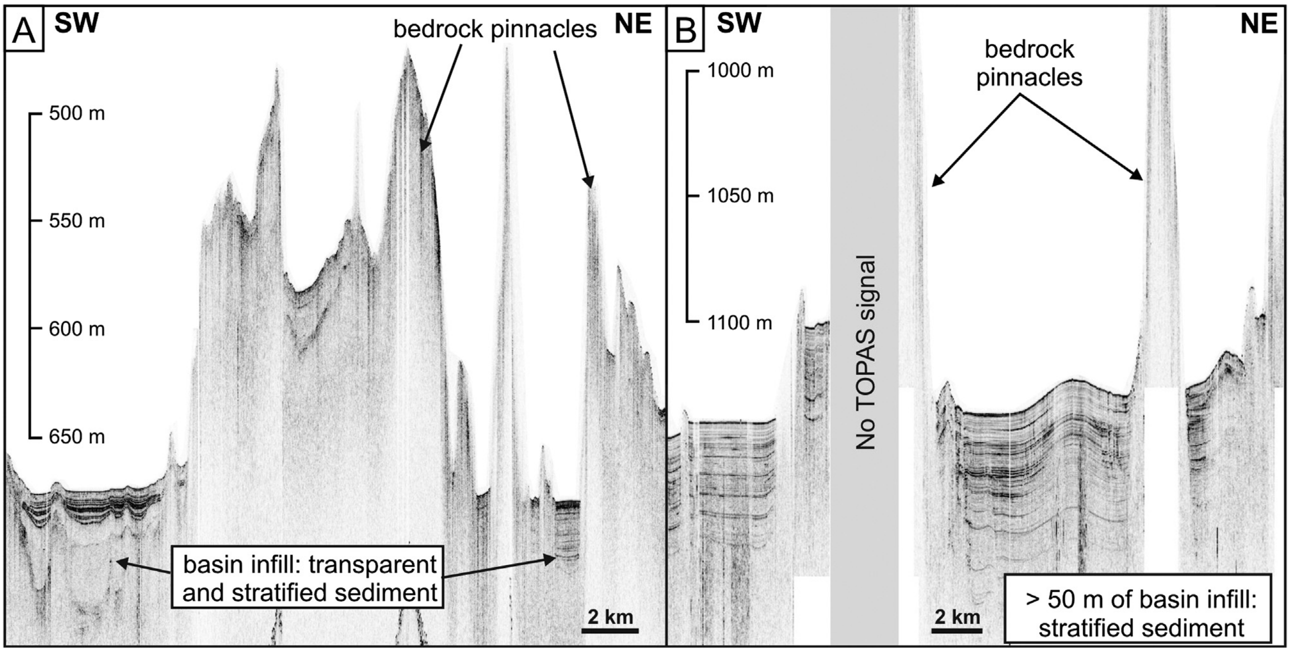


**Fig. 5.** TOPAS shallow-acoustic profiles along the axis of the inner fjord of the Uummannaq system (located in Fig. 7A). (A) From Karrat Isfjord, between 62 and 85 km from the margin of Rink Isbrae. (B) From Rink Fjord, between 10 and 30 km from the margin of Rink Isbrae.

facies which supports the interpretations given above. The inner part of the Uummannaq system, comprising the narrow Rink Fjord and Karrat Isfjord area (Fig. 4), is covered almost entirely by sediments of acoustic Facies B and S. Basins within the inner fjords are usually defined by highs or pinnacles of exposed bedrock (Fig. 5), sometimes draped by a thin veneer of sediment which may in some places be below the resolution of the TOPAS system. Between these bedrock highs, basins are typically infilled by stratified sediments of acoustic Facies S (Fig. 5); resedimentation from slopes, in addition to glacimarine rain-out, is likely to be an important process in these basins. The outer part of the fjord system and the innermost part of the shelf, east of about 55°W, is characterised by sediments of acoustic Facies D (Fig. 4), with occasionally stratified elements, interspersed with relatively scattered outcrops of bedrock (Fig. 6A). A mix of Facies S and D is also present over most of the continental shelf (Fig. 4); however, areas on the shallower banks to either side of the cross-shelf trough, and at one point where the trough itself shallows to less than about 510 m of water depth, the irregular sea floor is represented by Facies I (Fig. 4). Facies S and D are not identified from shallow bank areas. The continental slope is made up primarily of the transparent to semi-transparent lobate forms of Facies L, but the uppermost slope, to about 850 m is composed in part of the highly irregular surface reflection of Facies I. Facies N is found only in a relatively restricted area on the southern flank of the inner cross-shelf trough (Fig. 4).

It is clear from our shallow acoustic records that much of the glacimarine debris making up Facies S and D is underlain by a strong reflection and a unit of semi-transparent sediment (Fig. 6B). It is, however, difficult to correlate and map out this reflector over long distances. We interpret this underlying unit as subglacial till (Dowdeswell et al., 2004; Ó Cofaigh et al., 2005), which also has at its surface streamlined landforms typical of those produced at the base of former and modern fast-flowing ice streams (Clark, 1993; Ottesen et al., 2005; King et al., 2009). These underlying sediments were probably deposited when ice advanced down the fjord system and across the Uummannaq shelf during the last full-glacial period. Although often buried by several metres of glacimarine sediment deposited after ice-sheet retreat through the Uummannaq system, these landforms are not covered by sufficient debris to conceal their streamlined form in the direction of past ice flow (Fig. 6B).

## 5. Submarine landforms and sediments: description

### *5.1. Inner fjords*

The 85 km-long inner fjord system, comprising Rink Fjord and Karrat Isfjord, is characterised mainly by a relatively flat sea floor which is broken occasionally by bedrock pinnacles (Fig. 7). The deep basins of Rink Fjord reach over 1000 m in depth in much of the inner 50 km of the fjord (Fig. 7A). The sea-floor topography of bedrock pinnacles separating deep sedimentary basins is well-illustrated in the sub-bottom profiler records in Fig. 5; it is also found in, for example, in the inner fjords of the Scoresby Sund and Kejser Franz Josef Fjord systems in East Greenland (Ó Cofaigh et al., 2001; Evans et al., 2002). Karrat Isfjord, seaward of Rink Fjord, is generally less than 600 m deep, and, from its rougher bed topography, appears to have a greater proportion of exposed bedrock. The walls of the relatively narrow Rink Fjord, which is less than 3.6 km wide, are very steep and occasional lobate landforms are observed (Fig. 7B, red arrow).

The sea floor in the innermost 7 km of Rink Fjord, extending right to the terminus of Rink Isbrae, is shown in Fig. 7B. The image shows that there are two very deep basins, reaching over 1000 m, separated by a large transverse ridge that shallows to about 600 m and is about 200 m high (Fig. 7B, C). The ice-distal slope of this submarine ridge is steeper, at 22°, than the ice-proximal side, a morphology typical of many ice-contact sedimentary landforms (Benn and Evans, 2010). Inshore of the ridge, a deep trough is imaged in the centre of the fjord. Within this deep area there is evidence of two lineations that are elongate in the direction of ice flow. On the distal side of the large transverse ridge there are several poorly defined lobes which may represent debris flows mobilised from the steep distal face of the feature. A well-defined

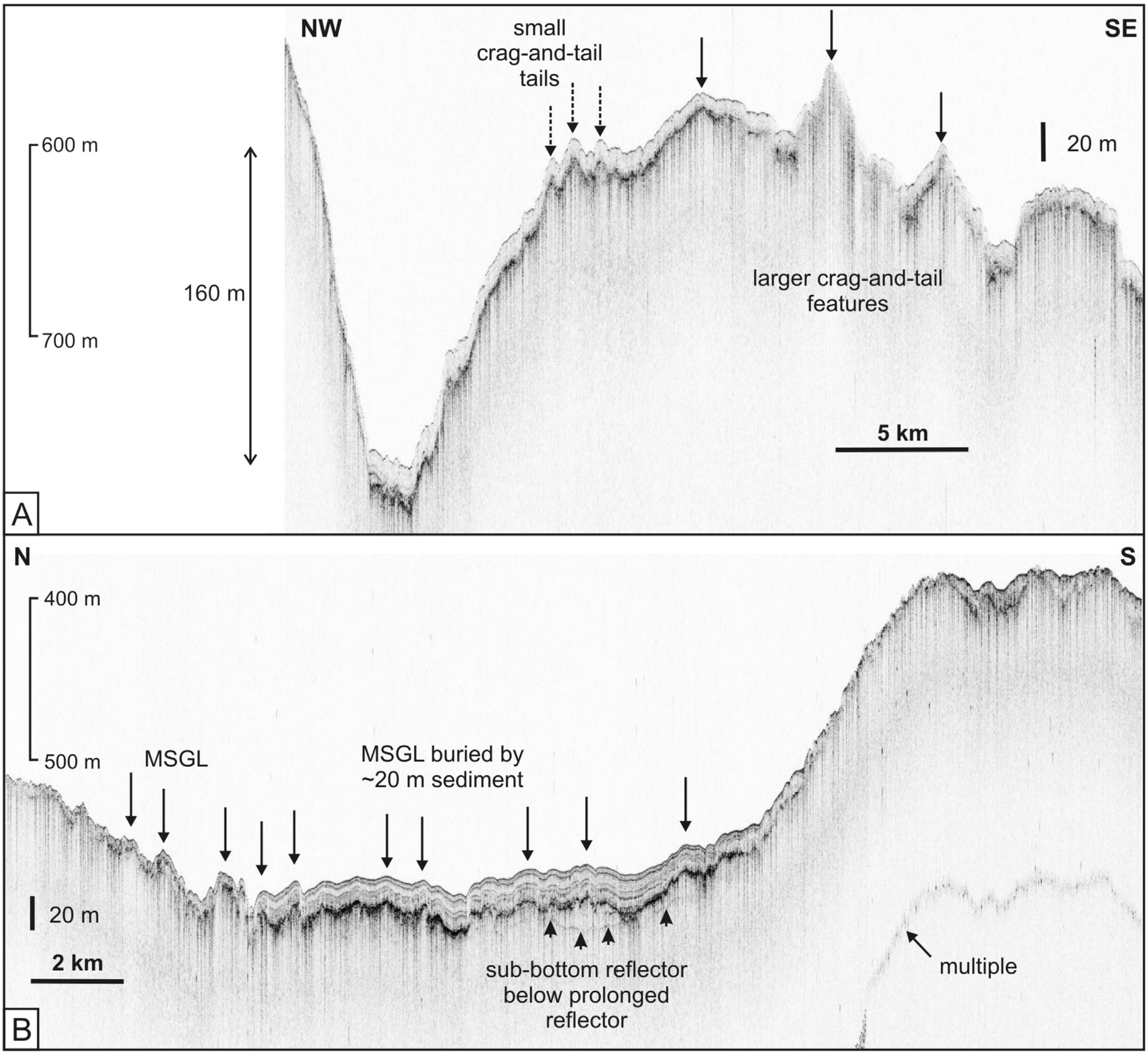


**Fig. 6.** TOPAS shallow-acoustic profiles from the outer fjord and inner shelf of the Uummannaq system (located in Fig. 8A). (A) Transect across streamlined submarine landforms in the outer fjord at 53°W. (B) Transect across the inner shelf at 55°W including the cross-shelf trough floor with streamlined sedimentary landforms, and shallower bank to the south.

submarine channel can also be traced for about 4 km seaward from the base of the transverse ridge (Fig. 7B). The channel is sinuous, and up to 350 m wide and 25 m deep, with a levee on one side (Fig. 7D).

### 5.2. Outer Uummannaq Fjord

The area of 1000 km$^2$ or so imaged in the outer part of Uummannaq Fjord using swath-bathymetric methods is shown in Fig. 8. This area exhibits the most varied array of sea-floor landforms found anywhere in the Uummannaq system. There is a series of streamlined features which are orientated generally along the axes of the fjords, although a clear curvi-linearity is superimposed on this overall pattern (Fig. 8A).

In the inner 20 km or so of Uummannaq Fjord, sedimentary streamlined lineations and bedrock-cored ‘crag-and-tail’ features are present (Fig. 8B); the distally narrowing sedimentary tails of the latter appear to have their origins in a bedrock ridge that curves across the fjord axis. The streamlined features also show clearly in a TOPAS profile; an approximately 10 m thick drape of semi-transparent sediment of acoustic facies D overlies the strong reflector in which the buried streamlined features are formed (Fig. 6A).

At and beyond the location where Uummannaq Fjord narrows to about 25 km wide, between Ubekendt Ejland and Nuussuaq Peninsula (Fig. 8A), the landform suite becomes more complex, although still streamlined in a generally east-west direction. The simple lineations of the inner part of Uummannaq Fjord (Fig. 8B) are replaced by an increasingly complex and more broken pattern of shorter linear features which trend first WNW and then WSW (Fig. 8C). The more irregular parts of the image probably represent bedrock at or close to the sea floor, and in the upper left of Fig. 8C there is an area of about 20 km$^2$ where several small channels appear to be present, separated by bedrock highs.

Further offshore, between about 30 and 60 km from the fjord mouth south of Ubekendt Ejland (Fig. 8A), the sea floor again

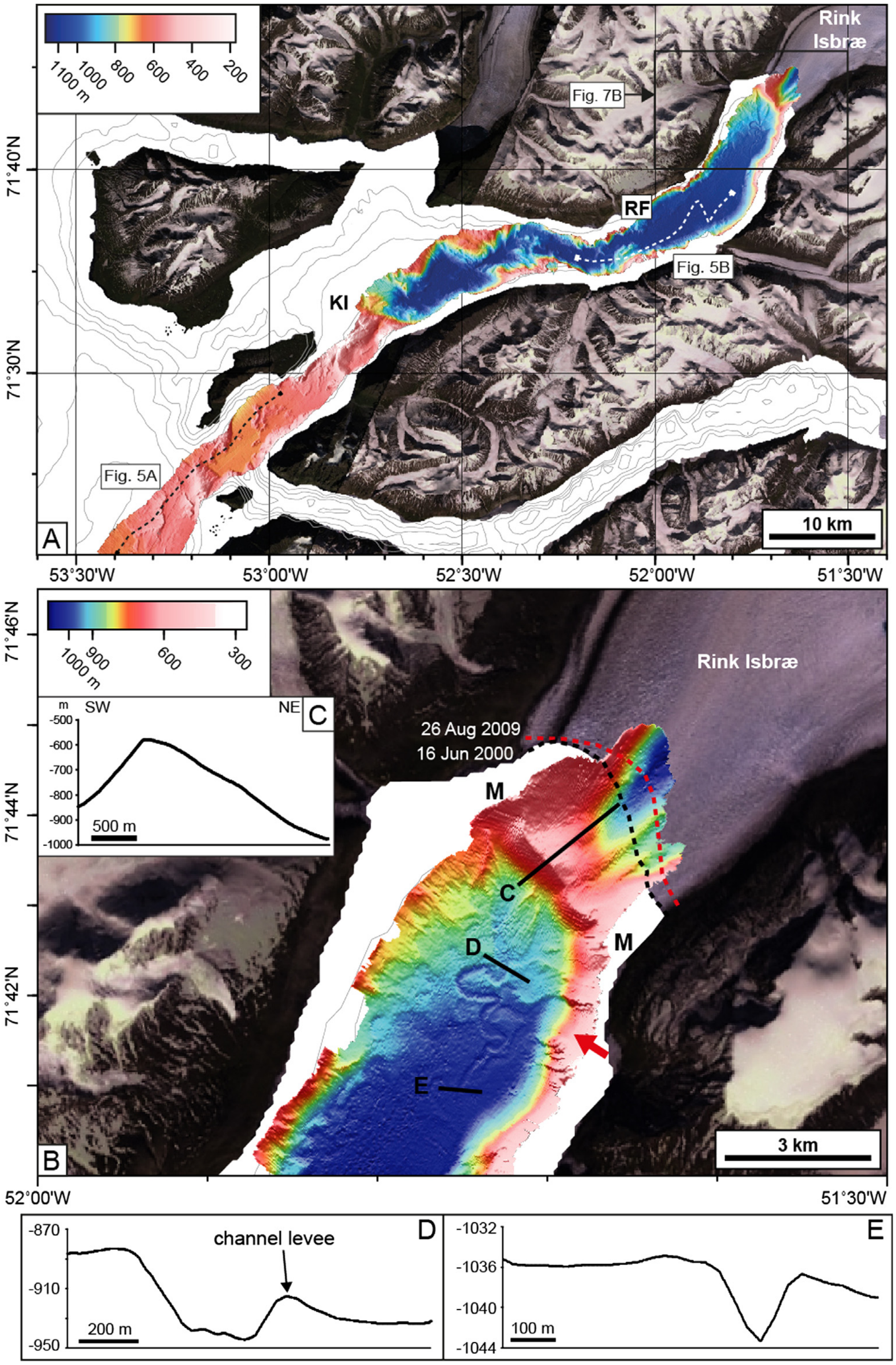


**Fig. 7.** Colour-shaded swath-bathymetric data from the inner fjord of the Uummannaq system. (A) Swath bathymetry of the innermost 85 km of the fjord system, known as Rink Fjord, with the terminus of Rink Isbrae shown (located in Fig. 1). RF is Rink Fjord and KI is Karrat Isfjord. (B) Enlarged image of the margin of Rink Isbrae (Landsat image from 16 June 2000) and swath data from the innermost 12 km of our swath coverage. M-M marks the position of a prominent cross-fjord ridge, interpreted as a glacial moraine. Note the sinuous submarine channel. The red arrow indicates an area of possible slope failure from the eastern side-wall of the fjord. (C) Elevation transect across the moraine ridge, showing its asymmetric profile in between 650 and almost 900 m of water. (D) and (E) Cross-sections of submarine channel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

becomes less complex, but remains dominated by linear to curvilinear streamlined features (Fig. 8D). These features appear to be sedimentary with little exposed bedrock. A number of the landforms have a drumlin-like character, with blunt-nosed landward faces and a streamlined tails that narrow seaward (Fig. 8D). Inshore of the head of each of the ten or so drumlins that are imaged there is a cresentic horseshoe-like depression that curves around the drumlin head (Fig. 8D). A north–south TOPAS profile across the

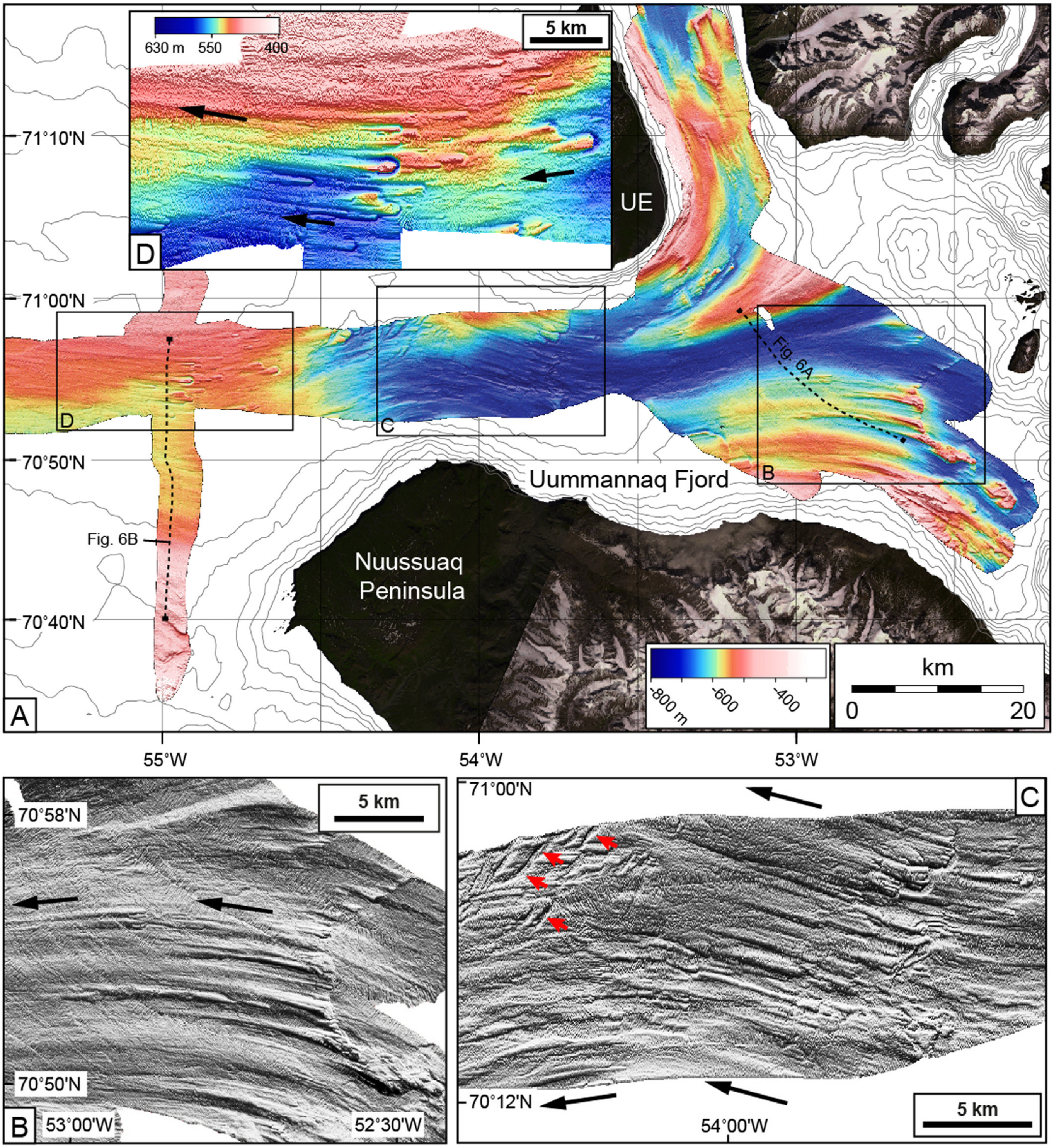


**Fig. 8.** Swath-bathymetric imagery of the outer fjord and inner shelf of the Uummannaq system. (A) Shaded-relief image of the geomorphology of outer Uummannaq Fjord (located in Fig. 1) with the positions of subsequent figures shown. (B) Imagery of streamlined landforms including crag-and-tail features. (C) Imagery of streamlined features and possible channels. (D) Colour-shaded bathymetric image of streamlined sediments and cresentic landforms. Black arrows in panels B, C and D indicate inferred directions of former ice flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

landforms again shows a strong and prolonged sub-bottom reflector which is lineated. Above this is an acoustically stratified drape of acoustic facies S that is up to about 20 m thick in the centre of the trough (Fig. 6B). The shallower bank at less than 500 m water depth on the north side of the trough appears to have an irregular surface, with furrows trending in several directions (Fig. 8D).

### 5.3. Uummannaq cross-shelf trough

Beyond the outer coast of central West Greenland, the Uummannaq cross-shelf trough continues for almost 200 km towards the shelf break and Baffin Bay with shallower banks of less than about 400 m water depth to the north and south (Fig. 1). The sea

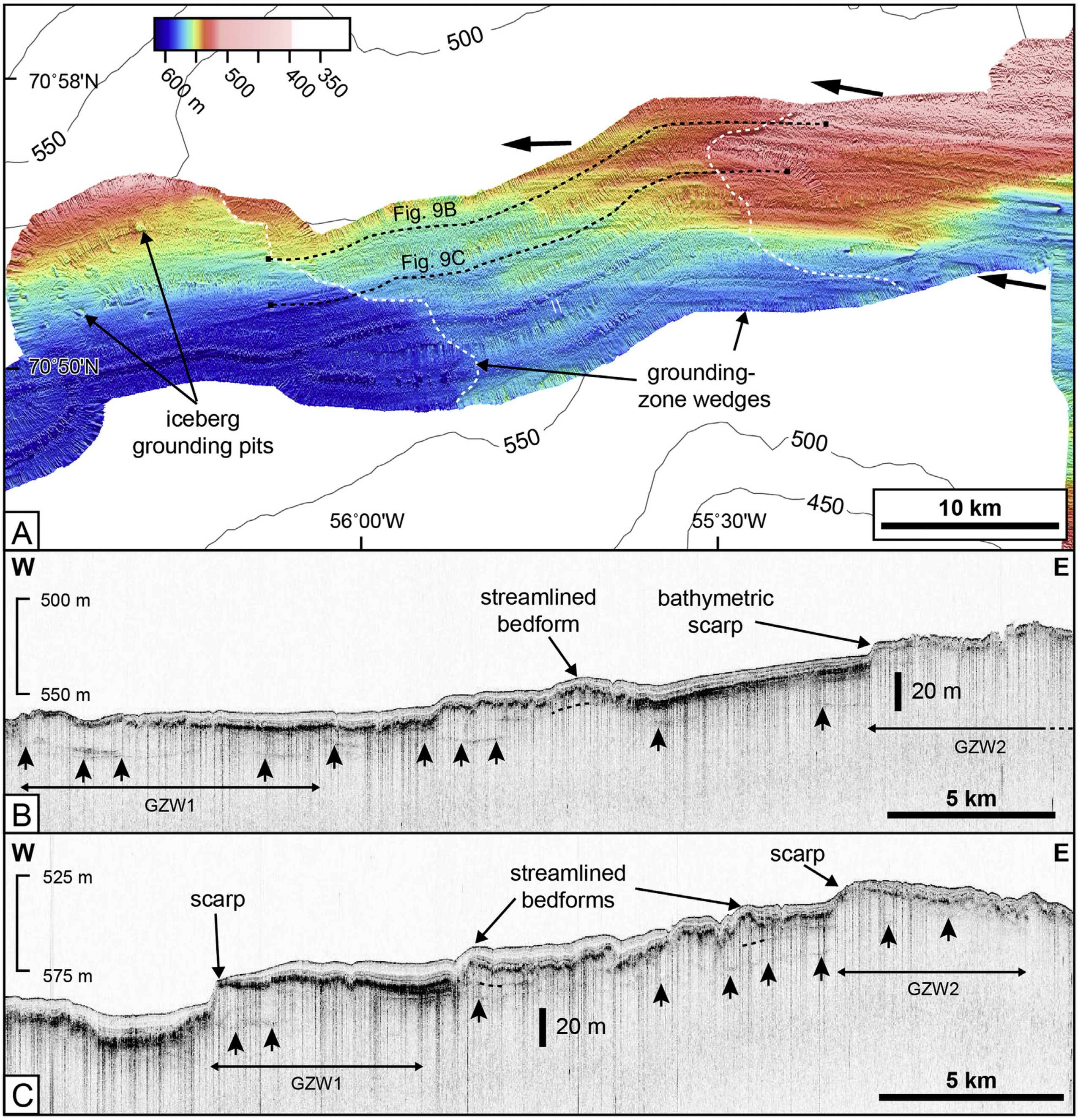


**Fig. 9.** (A) Swath-bathymetric imagery of the inner shelf of the Uummannaq system (located in Fig. 1). Streamlined sedimentary landforms, grounding-zone wedges (GZW) and iceberg grounding pits are shown. The axis of the cross-shelf trough is on the southern side of the image and the inferred direction of past ice flow is shown by black arrows. (B) and (C) Two TOPAS profiles along the trough axis (located in Fig. 9A), showing scarps defining the position of GZW. A faint sub-bottom reflector about 30 m below the sea floor is indicated by black vertical arrows.

floor in the cross-shelf trough, shown in Figs. 9 and 10, is relatively smooth compared with the outer fjord (Fig. 8). This morphological regularity, together with shallow sub-bottom profiles (Figs. 9B, C and 10B), indicates that the sea floor is made up almost entirely of sediments. This is supported by the seismic-reflection record of Fig. 2A, which shows that Uummannaq shelf comprises several hundred metres of prograding sediments.

There are occasional signs of streamlining in the direction of the cross-shelf trough axis, but streamlined landforms are not well-developed in the generally smooth sea floor of this area. The predominant topographic features are, instead, several bathymetric scarps or breaks of slope which are about 10–20 m high in the inner shelf area (Fig. 9). A further similar feature on the outer shelf has a 40 m-high scarp at its distal end (Fig. 10B). This feature has a clearly asymmetrical wedge-like shape along the trough axis, with a relatively steep seaward face and a much lower-gradient profile landward (Fig. 10B). The two features on the inner shelf have a less well-defined asymmetry (Fig. 9B); they are clearly draped with 10 m or so of acoustically semi-transparent or stratified sediment of acoustic facies D or S. This is underlain by a strong prolonged reflector and by one or more less continuous weaker sub-bottom reflectors (Fig. 9B, C). There is more limited evidence of a sub-

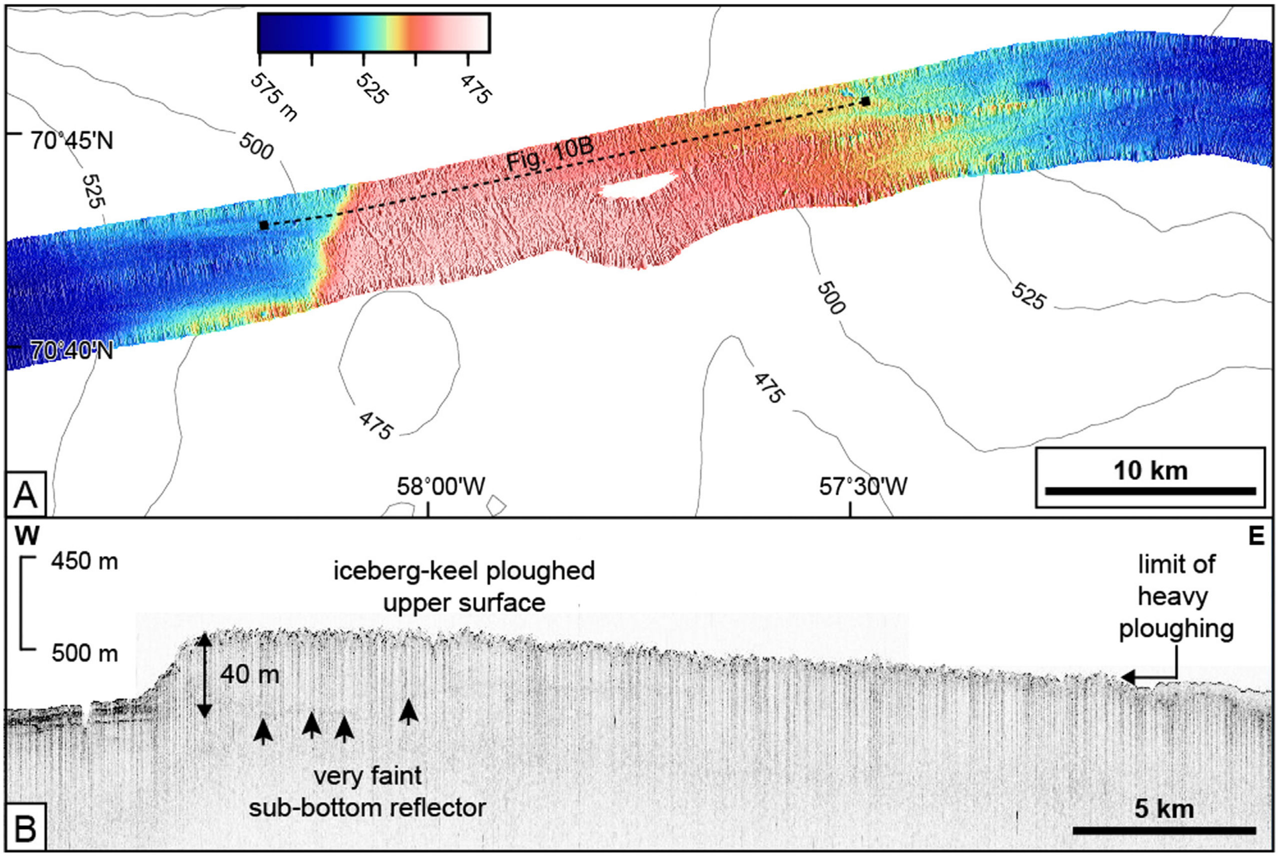


**Fig. 10.** The mid-shelf area of the Uummannaq system (located in Fig. 1). (A) Swath-bathymetric imagery showing a shallower area about 490 m deep, with deeper areas of the cross-shelf trough to west and east. (B) TOPAS shallow-acoustic profile showing a 40 m-high scarp and a highly irregular sea floor in the shallower water less than about 510 m deep.

bottom reflector beneath the outer-shelf wedge (Fig. 10B). This is probably because the surface of this wedge is very irregular, with multiple furrows on the scale of a few metres at water depths shallower than about 520 m (Fig. 10), and this acts to scatter energy and restrict penetration by the TOPAS system.

### 5.4. Outermost shelf and slope

The outermost part of Uummannaq shelf and, beyond it, the continental slope down to about 2000 m in Baffin Bay, are imaged in Fig. 11A. The sea floor of the outer shelf, to about 600 m depth, shows a series of streamlined sedimentary lineations that are orientated parallel to the long axis of the cross-shelf trough (Fig. 11A). The lineations are buried under a drape of acoustically stratified sediment (acoustic facies S) that reaches about 10 m in thickness and overlies a strong and prolonged reflector which represents the buried surface containing the lineations (Fig. 11B). The drape is not sufficiently thick, however, to obscure the lineated topography of the underlying surface. There is also a 10 m-high sedimentary ridge at approximately 60°W at about 600 m water depth. We have cored this ridge and the basal 12 cm of the 1.42 m-long core is composed of stiff diamict with glacimarine mud above (Ó Cofaigh et al., 2013a).

As the trough sides shallow towards less deep banks to the north and south of the cross-shelf trough (Fig. 1), sedimentary lineations are replaced by series of irregular furrows that are closely-spaced and typically a few metres deep; these irregular features dominate the sea-floor morphology of the outermost shelf at water depths of less than about 570 m (Fig. 11A). There are also a number of irregular furrows present at water depths down to about 850 m (Fig. 11A). The relatively sharp transition from lineations and an overlying sedimentary drape to banks whose surface is highly irregular on the scale of a few metres vertically is illustrated in the acoustic profile in Fig. 11B.

Beyond the shelf edge at about 600 m, the continental slope deepens to over 2000 m in Baffin Bay and is dominated by morphological features indicative of downslope sedimentary processes (Fig. 11A). There is a break of slope at about 950 m, where the slope steepens to a gradient of more than 2°. There is also evidence of lobate sedimentary features in the swath-bathymetric imagery and sub-bottom profiler records from the slope (Fig. 11A, C). TOPAS records show that sediment lobes are found stacked one on another, being most clearly identified below 1500 m depth (Fig. 11C). The upper part of the continental slope in Baffin Bay can be seen at the south-western limit of the profile in Fig. 11C; individual semi-transparent debris-flow units (of acoustic Facies L) can be traced right to the base of the slope.

## 6. Submarine landforms and sediments: interpretation

### 6.1. Inner fjord

#### 6.1.1. Smooth basin fill – meltwater sedimentation

The smooth sea floor of acoustically stratified facies S (Fig. 3), present between bedrock pinnacles over much of the inner fjord system in Rink Fjord and Karrat Isfjord (Figs. 6B and 7), is interpreted as fine-grained basin fill derived largely from meltwater delivery of sediment. The meltwater is derived from both fluvi-glacial and glacial sources. Large turbid subaerial meltwater streams were observed at the lateral margins of Rink Isbrae and

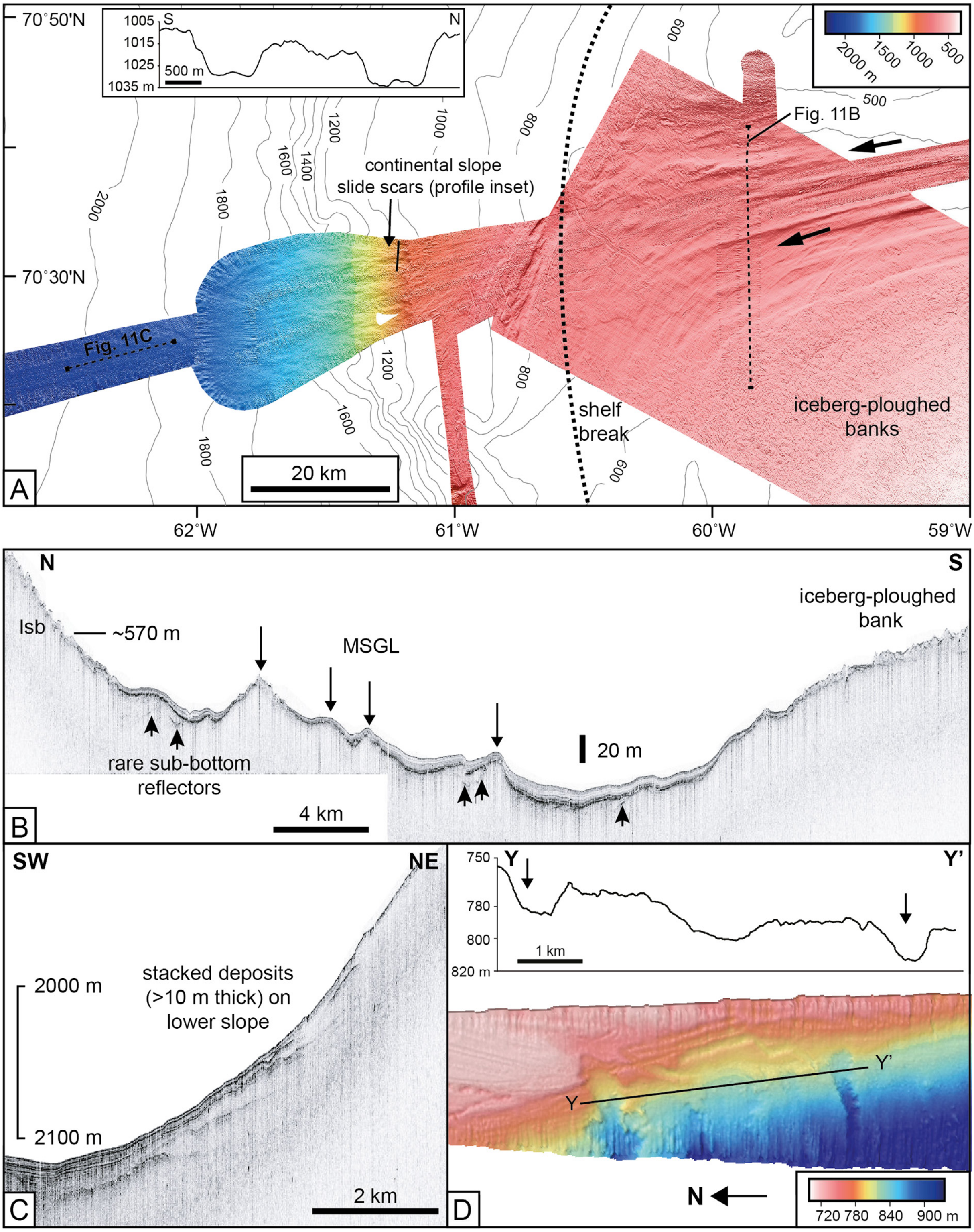


**Fig. 11.** The outer shelf and upper slope offshore of Uummannaq Fjord. (A) Swath-bathymetric imagery of the outermost shelf and upper continental slope; a S–N cross-section of two slide scars is inset. Fig. 11A and D are located in Fig. 1; Fig. 11B and C are located in Fig. 11A. (B) TOPAS shallow-acoustic profile across the outermost part of the cross-shelf trough. Streamlined mega-scale glacial lineations (MSGL) are shown (thin black arrows) and faint sub-bottom reflectors are indicated by black arrows with thicker heads. (C) Acoustic profile from the shelf edge down the slope. (D) Swath-bathymetric colour image of the upper slope. Note that the image is rotated with North to the left. Several downslope-orientated slide scars can be seen, below which are possible slope-parallel iceberg ploughmarks. The slide scar to the left appears to cross-cut the ploughmarks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

other tidewater glaciers during our cruise in August 2009, and glacifluvial streams draining from melting snow and smaller terrestrial glaciers were also present. Plumes of suspended sediment were also observed emerging at tidewater ice margins, implying an additional subglacial source for turbid meltwater (e.g. Powell, 1990; Mugford and Dowdeswell, 2011). Finally, melting of the many icebergs that traverse the inner fjord system also contributes to the delivery of sediment of all grain sizes to the water column (Mugford and Dowdeswell, 2010). On steeper slopes, adjacent to fjord side-walls and where bedrock is close to the sea floor, the floor of the inner fjords is more irregular and of acoustic facies B (Figs. 3, 6A and 7). Part of this irregularity may be due to the presence of sediment lobes that are interpreted as debris flows from slope failure on the steep fjord walls (Fig. 7B). Similar features are also observed in seismic profiles from Kejser Franz Joseph Fjord, East Greenland (Evans et al., 2002).

#### 6.1.2. Transverse ridges – moraines or bedrock

Some large transverse ridges contributing to the irregular appearance of the fjord floor in Karrat Isfjord appear to be predominantly composed of bedrock with a thin veneer of draping sediment (Fig. 8A). There is also a major ridge extending across the fjord between one and two kilometres from the present margin of Rink Isbrae that has a different appearance, however; it is about 100 m high and asymmetrical in long profile, with a relatively steep ice-distal face (Fig. 7B, C). The ice-proximal face of the ridge is of lower gradient and appears smooth, suggesting that the ridge is likely to be sedimentary. Penetration by the TOPAS system is limited, an indication that the material may be diamictic, consistent with an origin as a large ice-marginal transverse moraine ridge. Prominent lateral moraine ridges are also present onshore and are particularly well-developed on the north side of the margin of Rink Isbrae. The subaerial and submarine ridges are interpreted to mark the position of Rink Isbrae during the cool Little Ice Age (LIA) (e.g. Dowdeswell, 1995), which occurred in West Greenland between 1500 and 1860 (Dahl-Jensen et al., 1998; Fischer et al., 1998). Ice-front retreat since the LIA is typical of many West Greenland glaciers that terminate in fjords, although a number of land-based glaciers appear to have had a 20th century maximum (Kelley et al., 2012). The relatively large size of the submarine moraine ridge suggests that the glacier may have been in this position for at least a few decades. Ridge height and its smooth ice-proximal face suggest that it was formed as an ice-contact landform. Similar asymmetrical moraine ridges, observed within a few kilometres of modern tidewater glaciers in, for example, Svalbard and Chilean fjords, have also been interpreted to result from Little Ice Age glacier advances (e.g. Ottesen and Dowdeswell, 2009; Dowdeswell and Vasquez, 2013).

#### 6.1.3. Submarine channel – turbidity-current activity

A single submarine channel is observed in our swath-bathymetric imagery from the inner fjord system (Fig. 7B, C). Its upstream end is located about 1.5 km beyond the transverse moraine ridge. The channel is highly sinuous, about 4 km long and terminates on the very flat 1000 m-deep basin floor (Fig. 7B). It is interpreted as a turbidity-current channel, formed during the down-slope flow of dense and probably sediment-rich water that is probably produced by occasional slope failures of the relatively steep ice-distal face of the moraine ridge. There is some limited evidence of a debris-flow lobe on the distal ridge-face. Debris flows are known to translate downslope into less viscous turbidity currents in many Arctic fjords (e.g. Syvitski et al., 1987). Turbidity-current channels have also been observed to lose their identity when they reach the low-gradient floors of deep marine-sedimentary basins (e.g. Ó Cofaigh et al., 2004; Garcia et al., 2012).

### 6.2. Outer fjord and shelf

#### 6.2.1. Streamlined landforms – mega-scale glacial lineations (MSGL) and drumlins

Streamlined landforms orientated sub-parallel to the long axes of the outer fjord and cross-shelf trough are well-developed in several areas (Figs. 8 and 10). Three types of streamlined landform were observed. First, entirely sedimentary streamlined MSGLs, typically with an elongation ratio of >20:1, indicate the former presence of fast-flowing ice in the outer fjord and across the shelf right to the shelf break (Figs. 8 and 10A, B). The occurrence of these subglacially produced landforms demonstrates unequivocally that the Greenland Ice Sheet advanced to fill the whole of Uummannaq Trough and reached the shelf edge, probably at the LGM. Radiocarbon dates from the Uummannaq shelf and upper slope confirm that the MSGLs are linked to the presence of ice during the last full-glacial period (Jennings et al., 2013; Ó Cofaigh et al., 2013a). The 10 m-high moraine ridge on the outermost shelf yields a date of 14.8 cal. ka from 5 cm above the stiff diamict, which is interpreted as subglacial till (Ó Cofaigh et al., 2013a); the date suggests that deglacial retreat from a full-glacial maximum limit on the outermost shelf was underway by this time. The MSGL inshore of this moraine ridge on the shelf are buried under a drape of several metres of post-glacial fine-grained glacimarine sediment, indicating that they are relict features of the former ice stream. MSGLs have been reported in cross-shelf troughs in both polar regions (e.g. Canals et al., 2000; Ó Cofaigh et al., 2002; Ottesen et al., 2005), and have also been observed forming beneath fast-flowing ice streams in modern Antarctica (King et al., 2009). They are widely considered to be diagnostic of the former presence of fast-flowing ice streams (Clark, 1993). We also observe two recently formed streamlined landforms, likely to be MSGL, on the sea floor immediately beyond the modern terminus of Rink Isbrae (Fig. 7B).

A second type of streamlined landform is a number of crag-and-tail features (Benn and Evans, 2010), which have an ice-proximal rock core and a sedimentary tail elongated in the direction of ice flow. These distinctive features are found only in outer fjord at about 52.5°W (Fig. 8B). A number of these landforms appear to originate from a 15 km-long convex bedrock ridge on the sea floor, which presumably retarded ice flow and allowed the formation of the streamlined 'tail' down-flowline. The bedrock component of crag-and-tails presumably acted as an area of relatively high friction in what was otherwise a mainly sedimentary former glacier bed. Similar features have been reported from a number of Arctic fjords and the inner parts of cross-shelf troughs (e.g. Ottesen and Dowdeswell, 2009; Hogan et al., 2010), where bedrock is most likely to crop out at the sea floor. Further offshore, most high-latitude cross-shelf troughs are entirely sedimentary, given their build-up through the progradation of glacier-derived debris (Fig. 2A).

A third set of streamlined landforms, blunt-nosed sedimentary drumlins, again represent a sedimentary landform of subglacial origin (Benn and Evans, 2010). Their location, at about 55°W (Fig. 8A), is a little unusual. This is because drumlins are often found in the onset zones of former ice streams (Wellner et al., 2001; Lowe and Anderson, 2002). In this case, however, they are located in Uummannaq Trough, down-flow of well-developed MSGLs and crag-and-tail landforms (Fig. 8A). In addition, they are accompanied on their upstream side by cresentic depressions (Fig. 8D), whose process of formation remains largely unknown. The cresentic features could perhaps be related to subglacial water flow, since several palaeo-channels a few kilometres in length have also been identified on the inner shelf (Fig. 8C). Similar cresentic landforms associated with the stoss face of sedimentary drumlins have also been observed in Marguerite Trough, Antarctica, where a palaeo-ice stream is also demonstrated to have been present during the LGM (Ó Cofaigh et al., 2002; Kilfeather et al., 2011). Each of the three types of streamlined sedimentary landform is, nonetheless, an indicator of the presence of a former ice stream, together with its onset zone, in outer Uummannaq Fjord and Trough.

*6.2.2. Scarps and wedges – grounding-zone wedges (GZWs)*

Within Uummannaq Trough, the two sedimentary scarps between 55° and 56°W (Fig. 9), and a larger one at 58°W (Fig. 10), are interpreted as the relatively steep ice-distal faces of three GZWs. The much lower-gradient ice-proximal side of the GZWs at 58°W in particular shows the asymmetrical long-profile typical of many such features reported from other parts of the Greenland shelf (Dowdeswell and Fugelli, 2012). GZW are sedimentary wedges produced by the delivery of deforming subglacial sediment to a marine ice margin that has been stable in a similar location for decades or even centuries, often during more general deglacial retreat from a full-glacial position at the continental shelf edge (e.g. Mosola and Anderson, 2006; Dowdeswell and Fugelli, 2012). The faint sub-bottom reflector at the ice-distal end of the GZW in Fig. 10B indicates that this wedge may be up to about 40 m thick, whereas the inner-trough set of wedges are only 10–20 m thick. This suggests that the retreating ice margin may have been stable at each of these locations for only about half the time of the still-stand on the outer shelf, assuming a constant rate of delivery of deforming basal debris to the ice front. A further implication of the presence of GZWs is that deglacial retreat eastwards through Uummannaq Trough was episodic, and punctuated by at least three still stands, rather than taking place as a single catastrophic collapse event (Dowdeswell et al., 2008a; Ó Cofaigh et al., 2008).

*6.2.3. Irregular furrows – iceberg ploughmarks*

Irregular linear to curvilinear furrows dominate the morphology of the relatively shallow banks on either side of Uummannaq Trough. On the inner shelf banks, at about 55°W (Fig. 8C, D), in the shallowest parts of the trough itself (Fig. 9A, B), and on the top of a prominent GZW (Fig. 10A, B), the sea floor is typified by a chaotic pattern of furrows at depths shallower than about 520 m. On the outer-shelf banks, the 570 m depth contour appears to mark the lower limit of consistent iceberg-keel ploughing (Fig. 9A, B). Elsewhere, our swath-bathymetric coverage is in deeper water and furrows of similar morphology are largely absent except at the trough mouth (Fig. 11A).

The furrows are interpreted as ploughmarks produced when the submarine keels of large icebergs impinge on the sedimentary sea floor (Woodworth-Lynas et al., 1991). Similar iceberg ploughmarks have been observed over large areas of the Greenland shelf (Brett and Zarudzki, 1979; Dowdeswell et al., 1993; Syvitski et al., 2001; Evans et al., 2002, 2009). Several round depressions at about 56.5°W are probably grounding pits (Fig. 9A), where icebergs that are semi-buoyant occasionally impinge on the sea floor (e.g. Syvitski et al., 2001). The sharp cut-off in water depth, below which very little ploughing occurs, is probably a result of the thickness of the terminal ice cliffs from which icebergs drifting through the Uummannaq fjord-shelf system are calved; because the marine margins of ice sheets are usually a relatively uniform thickness, so too are the icebergs prior to fragmentation and melting during drift (Dowdeswell and Bamber, 2007). An abrupt water-depth limit to iceberg-keel ploughing has been observed on many polar and sub-polar continental shelves (e.g. Barnes and Lien, 1988; Metz et al., 2008; Dowdeswell et al., 2010; Sacchetti et al., 2012), and the control on iceberg dimensions exerted by the dimensions of the parent ice-sheet margin is also well-documented (Dowdeswell and Bamber, 2007). Icebergs with deeper keels are present only due to fragmentation and overturn, which may occasionally lead to iceberg geometries that result in particularly deep keels.

Some ploughmarks occur at the mouth of Uummannaq Trough down to about 850 m (Fig. 11A, D). Some of these deep ploughmarks appear to have been cut by subsequent scars and associated downslope depressions in the sea floor to the south of the mouth of Uummannaq Trough (Fig. 11D). The scars are inferred to mark the sites of at least three slope failures that took place subsequent to the formation of the iceberg ploughmarks. Isolated slope-parallel depressions up to about 40 m deep in from 850 to 1085 m of water on the West Greenland upper slope have also been ascribed to ploughing by huge icebergs probably produced during break-up of the last full-glacial ice sheet (Kuijpers et al., 2007). It is possible that several crude slope-parallel depressions at a little less than 800 m water depth at the mouth of Uummannaq Trough may be of a similar origin (Fig. 11A, D). Today, few icebergs with keels greater than about 500–600 m are calved from the fast-flowing ice streams and outlet glaciers of the Greenland Ice Sheet (Dowdeswell et al., 1992).

*6.3. Continental slope*

*6.3.1. Sediment lobes – downslope mass-wasting*

The continental slope at the mouth of Uummannaq Trough is characterised by lobate landforms interpreted as glacigenic debris flows. The debris flows are diamicts derived from sediment delivery to the shelf edge by the palaeo-ice stream that occupied the adjacent trough at the LGM (Fig. 11A) (Ó Cofaigh et al., 2013b). They appear to be stacked on the slope (Fig. 11C), and are major building blocks of a trough-mouth fan known as Uummannaq Fan (Ó Cofaigh et al., 2013b). Glacigenic debris flows, similar in acoustic character to those in Uummannaq Fan, are typically found within and at the surface of large trough-mouth fans containing tens of thousands of cubic kilometres of sediment on the continental margins of both the Arctic and Antarctic (e.g. Aksu and Hiscott, 1992; Laberg and Vorren, 1995; King et al., 1996; Vorren et al., 1998; Dowdeswell et al., 2008b); the fans offshore of Scoresby Sund and Disko Trough provide additional Greenland examples (Dowdeswell et al., 1997; Ó Cofaigh et al., 2013a). Sedimentological investigations on the northern sector of Uummannaq Fan show, however, that turbidity-current activity, together with iceberg-rafted and hemipelagic debris are also components of fan sedimentation (Ó Cofaigh et al., 2013b).

There is no evidence of turbidity-current channels on the part of Uummannaq Fan that we have imaged using swath bathymetry (Fig. 11A). This is in marked contrast to a well-developed set of such submarine channels that we have observed on Disko Fan, some 300 km to the south offshore of West Greenland. We have, as yet, no clear explanation for this very marked difference in process and form between these two large and adjacent West Greenland fan systems.

On the continental slope south of the Uummannaq cross-shelf trough, a series of small submarine slide scars is present (Fig. 11D). These scars indicate an additional mass-wasting process on the slope that delivers sediment downslope in this area; specific triggers for downslope transport at these depths could include small earthquakes, the build-up of excess pore pressures in slope sediments, or the removal of support at the foot of the slope by other processes (e.g. Baeten et al., 2013).

## 7. Discussion

*7.1. Submarine geomorphology and ice advance through the Uummannaq system*

The distribution of landforms within the Uummannaq fjord-shelf-slope system is summarised in Fig. 12A. Beyond the deep

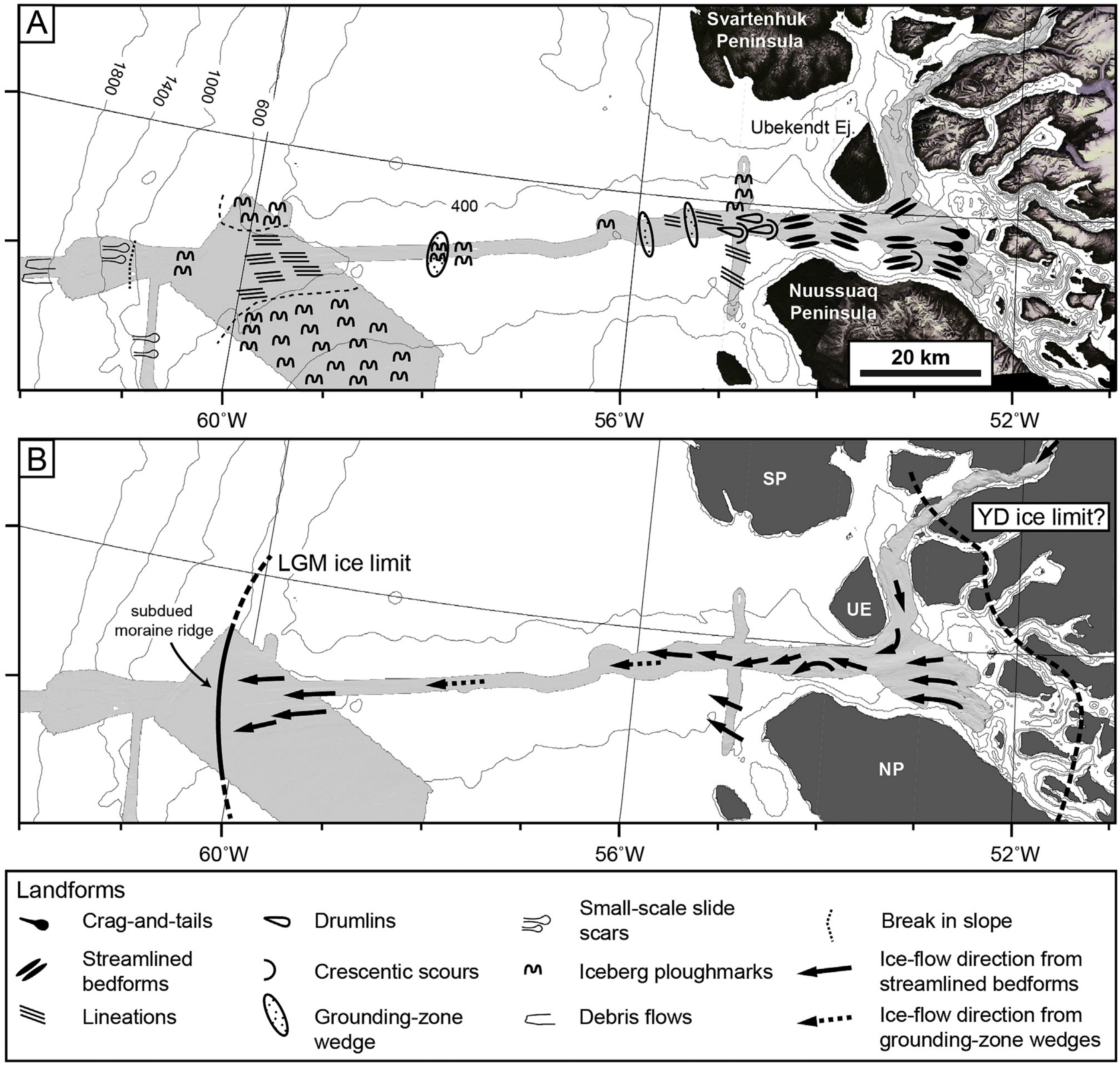


**Fig. 12.** Summary diagram of the locations of submarine landforms on the sea floor of the outer fjord, continental shelf and upper slope of the Uummannaq system, West Greenland (Fig. 1). (A) The distribution pattern of submarine landforms discussed in the text and illustrated in previous figures. (B) Former ice-flow directions inferred from the orientation of streamlined landforms and GZWs. Ice-sheet limits are drawn for the LGM based on this study and Ó Cofaigh et al. (2013a), and tentatively for the end of the Younger Dryas after Roberts et al. (2013). UE is Ubekendt Ejland.

inner fjords, which are blanketed by fine-grained basin fill between rock pinnacles, the suite of subglacially produced streamlined landforms can be used to reconstruct the direction of past, presumably full-glacial ice flow in Fig. 12B. The distribution of streamlined landforms, and a subdued moraine ridge at the mouth of Uummannaq Trough (Fig. 12B) (Ó Cofaigh et al., (2013a), demonstrates that a fast-flowing full-glacial ice stream was present and reached the shelf edge on this part of the West Greenland margin. The streamlined subglacial landforms vary in detailed morphology from crag-and-tail features, together with well-defined MSGLs, in the outer fjord, to less well-defined lineations on the inner and outer shelf. There is also an area of drumlins and accompanying cresentic depressions found mainly in the inner shelf, and additionally in a small area on the south side of the outer fjord. These are certainly subglacial landforms, but the precise role of meltwater in their mode of formation remains unclear. We suggest that the crescentic overdeepening is probably best explained by localised subglacial meltwater erosion (cf. Ó Cofaigh et al., 2010). The set of streamlined landforms described above is indicative of the deformation of water-saturated sediments at the bed of a former ice stream; some small channels and the cresentic depressions give additional support to the view that ice in the outer fjord and trough was at the pressure melting point at the bed.

The distribution of these well-preserved subglacial landforms demonstrates clearly that a fast-flowing ice stream advanced through the fjord system and onto the outermost shelf in Uummannaq cross-shelf trough. Radiocarbon dates indicate that this advance took place at the LGM (Ó Cofaigh et al., 2013a). The limited swath-bathymetric data we have from the adjacent shallower banks to either side of the ice stream, and the fact that they are almost entirely reworked by the ploughing action of iceberg keels (Fig. 12A), means that we can say little about ice extent and character on the continental shelf beyond the trough. This is an obvious target for further investigation.

The distribution of subglacial landforms, with the fjords and inner shelf of the Uummannaq system containing a mix of sediments and bedrock at the sea floor, and the outer shelf being entirely sedimentary, is typical of a number of major ice-stream systems in both the Arctic and Antarctic (e.g. Canals et al., 2000; Wellner et al., 2001; Lowe and Anderson, 2002; Ó Cofaigh et al., 2002; Evans et al., 2004, 2005; Dowdeswell et al., 2010). Drumlins and crag-and-tail bedforms have been interpreted as indicating the onset zone of fast ice-stream flow by some previous workers (e.g. Wellner et al., 2001). The association between form and flow is less clear in the Uummannaq system, given that some drumlins are found at about 55°W at the wide mouth of outer Uummannaq Fjord (Fig. 12A). The presence of cresentic depressions on the stoss side of some drumlins, and limited development of channels nearby (Fig. 8C, D), certainly relates to subglacial processes, but whether to an onset zone or to full ice-stream flow remains unclear.

### 7.2. Deglacial ice retreat

Ice retreat from its full-glacial maximum extent at the mouth of Uummannaq Trough had begun by 14.8 cal. ka ago (Fig. 1). The nature and rate of ice-stream retreat is important to understand from the point of view of both ice dynamics and implications for numerical-model reconstructions, and for the contribution of major ice-sheet drainage basins to the rapid global sea-level rise taking place over this period (e.g. Dowdeswell et al., 2008a; Ó Cofaigh et al., 2008; Carlson and Clark, 2012). The presence of three GZWs on the floor of Uummannaq Trough (Fig. 12A) suggests that ice-stream retreat was episodic and punctuated by at least this number of still-stands which allowed the build-up of sediments about 40 m thick in one case; this wedge probably took decades to centuries to develop, when the rates of sediment delivery at the base of modern ice streams are considered (e.g. Engelhardt and Kamb, 1997; Alley et al., 2007; Dowdeswell and Fugelli, 2012). We can also infer, from the presence of GZWs, that the Uummannaq ice stream did not retreat catastrophically through the cross-shelf trough as a single event driven, arguably, by a combination of rapid ice-stream thinning and global sea-level rise (Dowdeswell et al., 2008a). In fact, a date of 10.9 cal ka some 80 km offshore of Ubekendt Ejland (Fig. 1; McCarthy, 2011), suggests that ice had retreated from most of Uummannaq shelf by this time, supporting the idea of an episodic rather than catastrophic retreat of the ice stream (Ó Cofaigh et al., 2013a). In addition, the lack of large numbers of small transverse-to-flow sediment ridges in the trough suggests that retreat between GZWs may have been relatively rapid; the slow retreat of a grounded ice margin through, for example, some troughs in the Ross Sea in Antarctica or Bellsund in Svalbard (Shipp et al., 1999, 2002; Dowdeswell et al., 2008a; Ó Cofaigh et al., 2008), probably did not take place in Uummannaq Trough. There is little evidence of major ice-marginal features, and hence for extended still-stands, in the inner fjord system, except for the major moraine ridge marking a probable LIA maximum position near the present ice front of Rink Isbrae (Fig. 7B).

## 8. Conclusions

- Sea-floor landforms and accompanying acoustic-stratigraphic records allow interpretation of the past form and flow of a major westward-draining ice stream of the Greenland Ice Sheet, Rink Isbrae (Fig. 1), including both its former extent across the West Greenland shelf and its flow regime and style of deglaciation.
- The Late Pliocene–Pleistocene glacial package is a several hundred-metres-thick prograding wedge which down-laps onto an upper Miocene horizon (Fig. 2A). The upper parts of the dipping reflections are often eroded by subsequent glacial advances that produced Uummannaq cross-shelf trough (Fig. 2B).
- Several acoustic facies are mapped from sub-bottom profiler records of the 400 km-long Uummannaq fjord-shelf-slope system (Figs. 3 and 4). An acoustically stratified facies (Facies S; Fig. 5B), and its correlative Facies D, cover much of the fjord and trough floor (Fig. 4). They are interpreted as glacimarine sediment derived mainly from rain-out of fine-grained suspended sediment from turbid meltwater plumes. A strong and prolonged reflector buried beneath the stratified facies is interpreted as the surface of a semi-transparent deformation till unit, which includes streamlined landforms produced at the base of a former ice stream (Fig. 6B).
- The distribution of landforms within the Uummannaq fjord-shelf-slope system is used to reconstruct the direction of past, presumably full-glacial ice flow (Fig. 12). The presence of streamlined landforms (MSGL, drumlins, crag-and-tails; Figs. 8 and 11) demonstrates that a fast-flowing ice stream advanced through the fjord system to fill the whole of Uummannaq Trough, reaching the shelf edge on this part of the West Greenland margin. Radiocarbon dating indicates that this advance took place at the LGM (Ó Cofaigh et al., 2013a). These streamlined landforms are indicative of the deformation of water-saturated sediments at the bed of a former ice stream.
- There is a major sedimentary fan at the mouth of Uummannaq Trough, characterised by lobate sediments interpreted as glacigenic debris flows (Fig. 11). The debris flows are diamicts derived from sediment delivery to the shelf edge by the palaeo-ice stream that occupied the adjacent trough at the LGM. There is no evidence of turbidity-current channels on the part of Uummannaq Fan we have surveyed (Fig. 11A), contrasting to a well-developed set of submarine channels on Disko Fan, about 300 km to the south.
- Ice retreat from the mouth of Uummannaq Trough had begun by 14.8 cal. ka ago. GZWs on the floor of Uummannaq Trough (Figs. 9C, 10B and 12A) suggest that ice-stream retreat across the West Greenland shelf was episodic and punctuated by several still-stands which allowed the build-up of these depocentres over decades to centuries. Ice retreat between GZWs may have been relatively rapid. There is little sedimentary evidence for still-stands in the inner fjord system, except for the major moraine ridge marking a probable Little Ice Age maximum position near the present terminus of Rink Isbrae (Fig. 7B).
- On the shallow banks either side of Uummannaq Trough (Fig. 12A), a rough surface of irregular furrows (Acoustic Facies I, Fig. 3) is interpreted as ploughmarks produced when large iceberg keels impinge on the sedimentary sea floor (Fig. 11A and B). Reworking by iceberg keels means that any pre-existing glacial landforms have been largely destroyed; we can therefore say little about past ice flow on these banks.

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## References


Aksu, A.E., Hiscott, R.N., 1992. Shingled Quaternary debris flow lenses on the north-east Newfoundland slope. Sedimentology 39, 193–206.

Alley, R.B., Anandakrishnan, S., Dupont, T.K., Parizek, B.R., Pollard, D., 2007. Effect of sedimentation on ice-sheet grounding-line stability. Science 315, 1838–1841.

Baeten, N.J., Laberg, J.S., Forwick, M., Vorren, T.O., Vanneste, M., Forsberg, C.F., Kvalstad, T.J., Ivanov, M., 2013. Morphology and origin of smaller-scale mass movements on the continental slope off northern Norway. Geomorphology. http://dx.doi.org/10.1016/j.geomorph.2013.01.008.

Barnes, P.W., Lien, R., 1988. Icebergs rework shelf sediments to 500 m off Antarctica. Geology 16, 1130–1133.

Batchelor, C.L., Dowdeswell, J.A., 2013. The physiography of High Arctic cross-shelf troughs. Quat. Sci. Rev. (in press).

Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation, second ed. Arnold, London.

Bennike, O., Bjork, S., 2002. Chronology of the last recession of the Greenland Ice Sheet. J. Quat. Sci. 17, 211–219.

Brett, C.P., Zarudzki, E.F.K., 1979. Project Westmar, a Shallow Marine Geophysical Survey on the West Greenland Shelf. Rapport Grønlands Geologiske Undersøgelse, 87, 27 pp.

Canals, M., Urgeles, R., Calafat, A.M., 2000. Deep sea floor evidence of past ice streams off the Antarctic Peninsula. Geology 28, 31–34.

Carlson, A.E., Clark, P.U., 2012. Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation. Rev. Geophys. 50. http://dx.doi.org/10.1029/2011RG000371.

Clark, C.D., 1993. Mega-scale glacial lineations and cross-cutting ice-flow landforms. Earth Surf. Process. Landforms 18, 1–19.

Clark, P.U., Mix, A.C., 2002. Ice sheets and sea level of the Last Glacial Maximum. Quat. Sci. Rev. 21, 1–7.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W., Balling, N., 1998. Past temperatures directly from the Greenland Ice Sheet. Science 282, 268–271.

Dowdeswell, J.A., 1995. Glaciers in the High Arctic and recent environmental change. Phil. Trans. R. Soc. Lond. Ser. A 352, 321–334.

Dowdeswell, J.A., Bamber, J.L., 2007. Keel depths of modern Antarctic icebergs and implications for sea-floor scouring in the geological record. Mar. Geol. 243, 120–131.

Dowdeswell, J.A., Fugelli, E.M.G., 2012. The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets. Geol. Soc. Am. Bull. 124, 1750–1761.

Dowdeswell, J.A., Vasquez, M., 2013. Submarine landforms in the fjords of southern Chile: implications for glacimarine processes and sedimentation in a mild glacier-influenced environment. Quat. Sci. Rev. 64, 1–19.

Dowdeswell, J.A., Whittington, R.J., Hodgkins, R., 1992. The sizes, frequencies and freeboards of East Greenland icebergs observed using ship radar and sextant. J. Geophys. Res. 97, 3515–3528.

Dowdeswell, J.A., Villinger, H., Whittington, R.J., Marienfeld, P., 1993. Iceberg scouring in Scoresby Sund and on the East Greenland continental shelf. Mar. Geol. 111, 37–53.

Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.-J., Mienert, J., Siegert, M.J., 1996. Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: long-range side-scan sonar evidence. Geophys. Res. Lett. 23, 3535–3538.

Dowdeswell, J.A., Kenyon, N.H., Laberg, J.S., 1997. The glacier-influenced Scoresby Sund Fan, East Greenland continental margin: evidence from GLORIA and 3.5 kHz records. Mar. Geol. 143, 207–221.

Dowdeswell, J.A., Ó Cofaigh, C., Pudsey, C.J., 2004. Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream. Geology 32, 13–16.

Dowdeswell, J.A., Ottesen, D., Rise, L., Craig, J., 2007. Identification and preservation of landforms diagnostic of past ice-sheet activity on continental shelves from three-dimensional seismic evidence. Geology 35, 359–362.

Dowdeswell, J.A., Ottesen, D., Evans, J., Ó Cofaigh, C., Anderson, J.B., 2008a. Submarine glacial landforms and rates of ice-stream collapse. Geology 36, 819–822.

Dowdeswell, J.A., Ó Cofaigh, C., Noormets, R., Larter, R.D., Hillenbrand, C.-D., Benetti, S., Evans, J., Pudsey, C.J., 2008b. A major trough-mouth fan on the continental margin of the Bellingshausen Sea, West Antarctica: Belgica Fan. Mar. Geol. 252, 129–140.

Dowdeswell, J.A., Evans, J., Ó Cofaigh, C., 2010. Submarine landforms and shallow acoustic stratigraphy of a 400 km-long fjord-shelf-slope transect, Kangerlussuaq margin, East Greenland. Quat. Sci. Rev. 29, 3359–3369.

Engelhardt, H., Kamb, B., 1997. Basal hydraulic system of a West Antarctic ice stream: constraints from borehole observations. J. Glaciol. 43, 207–230.

Evans, J., Dowdeswell, J.A., Grobe, H., Niessen, F., Stein, R., Hubberten, H.W., Whittington, R.J., 2002. Late Quaternary sedimentation in Kejser Franz Joseph Fjord and the continental margin of East Greenland. In: Dowdeswell, J.A., Ó Cofaigh, C. (Eds.), Glacier-influenced Sedimentation on High-latitude Continental Margins, Geological Society of London, Special Publication 203, pp. 149–179.

Evans, J., Dowdeswell, J.A., Ó Cofaigh, C., 2004. Late Quaternary submarine bedforms and ice-sheet flow in Gerlache Strait and on the adjacent continental shelf, Antarctic Peninsula. J. Quat. Sci. 19, 397–407.

Evans, J., Pudsey, C.J., Ó Cofaigh, C., Morris, P.W., Domack, E.W., 2005. Late Quaternary glacial history, dynamics and sedimentation of the eastern margin of the Antarctic Peninsula Ice Sheet. Quat. Sci. Rev. 24, 741–774.

Evans, J., Ó Cofaigh, C., Dowdeswell, J.A., Wadhams, P., 2009. Marine geophysical evidence for former expansion and flow of the Greenland Ice Sheet across the north-east Greenland continental shelf. J. Quat. Sci. 24, 279–293.

Fischer, H., Werner, M., Wagenbach, D., Schwager, M., Thorsteinnson, T., Wilhelms, F., Kipfstuhl, J., Sommer, S., 1998. Little Ice Age clearly recorded in northern Greenland ice cores. Geophys. Res. Lett. 25, 1749–1752.

Fleming, K., Lambeck, K., 2004. Constraints on the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models. Quat. Sci. Rev. 23, 1053–1077.

Funder, S., Hansen, L., 1996. The Greenland ice sheet – a model for its culmination and decay during and after the Last Glacial Maximum. Bull. Geol. Soc. Den. 42, 137–152.

Funder, S., Kjeldsen, K.K., Kjær, K., Ó Cofaigh, C., 2011. The Greenland Ice Sheet during the past 300,000 years: A review. In: Ehlers, J., Gibbard, P., Hughes, P.D. (Eds.), Quaternary Glaciations—Extent and Chronology. Part IV: a Closer Look, Developments in Quaternary Science, vol. 15. Elsevier, Amsterdam, pp. 699–713.

Garcia, M., Dowdeswell, J.A., Ercilla, G., Jakobsson, M., 2012. Recent glacially influenced sedimentary processes on the East Greenland continental slope and deep Greenland Basin. Quat. Sci. Rev. 49, 64–81.

Henriksen, N., 2008. Geological History of Greenland. Four Billion Years of Earth Evolution. GEUS, 272 pp.

Hogan, K.A., Dowdeswell, J.A., Noormets, R., Evans, J., Ó Cofaigh, C., Jakobsson, M., 2010. Submarine landforms and ice-sheet flow in the Kvitøya Trough, northwestern Barents Sea. Quat. Sci. Rev. 29, 3563–3582.

Hogan, K.A., Dix, J.K., Lloyd, J.M., Long, A.J., Cotterill, C.J., 2011. Seismic stratigraphy records the deglacial history of Jakobshavn Isbrae, West Greenland. J. Quat. Sci. 26, 757–766.

Hogan, K.A., Dowdeswell, J.A., Ó Cofaigh, C., 2012. Glacimarine sedimentary processes and depositional environments in an embayment bed by West Greenland ice streams. Mar. Geol. 311, 1–16.

Jakobsson, M., Mayer, L.A., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H.-W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O.B., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G., Weatherall, P., 2012. The International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0. Geophys. Res. Lett. 39, L12609. http://dx.doi.org/10.1029/2012GL052219.

Jennings, A.E., Walton, M.E., Ó Cofaigh, C., Kilfeather, A., Andrews, J.T., Ortiz, J.D., de Vernal, A., Dowdeswell, J.A., 2013. Paleoenvironments during the Younger Dryas–Early Holocene retreat of the Greenland Ice Sheet from outer Disko Trough, central west Greenland. J. Quat. Sci. http://dx.doi.org/10.1002/jqs.2652.

Kelley, S.E., Briner, J.P., Young, N.E., Babonis, G.S., Csatho, B., 2012. Maximum late Holocene extent of the western Greenland Ice Sheet during the late 20th century. Quat. Sci. Rev. 56, 89098.

Kelly, M., 1985. A review of the Quaternary geology of western Greenland. In: Andrews, J.T. (Ed.), Quaternary Environments Eastern Canadian Arctic, Baffin Bay and Western Greenland. Allen and Unwin, Boston, pp. 461–501.

Kilfeather, A.A., Ó Cofaigh, C., Lloyd, J.M., Dowdeswell, J.A., Xu, S., Moreton, S.G., 2011. Ice-stream retreat and ice-shelf history in Marguerite Trough, Antarctic Peninsula: sedimentological and foraminiferal signatures. Geol. Soc. Am. Bull. 123, 997–1015.

King, E.L., Sejrup, H.P., Haflidason, H., Elverhøi, A., Aarseth, I., 1996. Quaternary seismic stratigraphy of the North Sea Fan: glacially-fed gravity flow aprons, hemipelagic sediments, and large submarine slides. Mar. Geol. 130, 293–315.

King, E.C., Hindmarsh, R.C.A., Stokes, C.R., 2009. Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream. Nat. Geosci. 2, 585–588.

Kuijpers, A., Dalhoff, F., Brandt, M.P., Hümbs, P., Schott, T., Zotova, A., 2007. Giant iceberg plow marks at more than 1 km water depth offshore West Greenland. Mar. Geol. 246, 60–64.

Laberg, J.S., Vorren, T.O., 1995. Late Weichselian submarine debris flow deposits on the Bear Island Trough Mouth Fan. Mar. Geol. 127, 45–72.

Long, A.J., Roberts, D.H., Dawson, S., 2006. Early Holocene history of the west Greenland Ice Sheet and the GH-8.2 event. Quat. Sci. Rev. 25, 904–922.

Lowe, A.L., Anderson, J.B., 2002. Reconstruction of the West Antarctic ice sheet in Pine Island Bay during the Last Glacial Maximum and its subsequent retreat history. Quat. Sci. Rev. 21, 1879–1897.

McCarthy, D., 2011. Late Quaternary Ice-ocean Interactions in Central West Greenland. PhD thesis. Department of Geography, University of Durham, UK.

Metz, J.M., Dowdeswell, J.A., Woodworth-Lynas, C.M.T., 2008. Sea-floor scour at the mouth of Hudson Strait by deep-keeled icebergs from the Laurentide Ice Sheet. Mar. Geol. 253, 149–159.

Mosola, A.B., Anderson, J.B., 2006. Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? Quat. Sci. Rev. 25, 2177–2196.

Mugford, R.I., Dowdeswell, J.A., 2010. Modeling iceberg-rafted sedimentation in high-latitude fjord environments. J. Geophys. Res. 115. http://dx.doi.org/10.1029/2009JF001564.

Mugford, R.I., Dowdeswell, J.A., 2011. Modeling glacial meltwater plume dynamics and sedimentation in high-latitude fjords. J. Geophys. Res. 116, F01023. http://dx.doi.org/10.1029/2010JF001735.

Ó Cofaigh, C., Dowdeswell, J.A., Grobe, 2001. Holocene glacimarine sedimentation, inner Scoresby Sund, East Greenland: the influence of fast-flowing ice-sheet outlet glaciers. Mar. Geol. 175, 103–129.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., Morris, P., 2002. Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf. Geophys. Res. Lett. 29. http://dx.doi.org/10.1029/2001. GL014488.
Ó Cofaigh, C., Taylor, J., Dowdeswell, J.A., Pudsey, C.J., 2003. Palaeo-ice streams, trough-mouth fans and high-latitude continental slope sedimentation. Boreas 32, 37–55.
Ó Cofaigh, C., Dowdeswell, J.A., Kenyon, N.H., Evans, J., Taylor, J., Mienert, J., Wilken, M., 2004. Timing and significance of glacially-influenced mass wasting in the submarine channels of the Greenland Basin. Mar. Geol. 207, 39–54.
Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Hiemstra, J., Pudsey, C.J., Evans, J., Evans, D.J.A., 2005. Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream. Quat. Sci. Rev. 24, 709–740.
Ó Cofaigh, C., Dowdeswell, J.A., Evans, J., Larter, R.D., 2008. Geological constraints on Antarctic palaeo-ice stream retreat rates. Earth Surf. Process. Landforms 33, 513–525.
Ó Cofaigh, C., Dowdeswell, J.A., King, E., Anderson, J.B., Clark, C.D., Evans, D.J.A., Evans, J., Hindmarsh, R.C.A., Larter, R.D., Stokes, C.R., 2010. Comment on Shaw J., Pugin, A. and Young, R., 2008: "A meltwater origin for Antarctic shelf bedforms with special attention to megalineations" Geomorphology 102, 364–375. Geomorphology 117, 195–198.
Ó Cofaigh, C., Dowdeswell, J.A., Jennings, A.E., Hogan, K.A., Kilfeather, A.A., Hiemstra, J.F., Noormets, R., Evans, J., McCarthy, D.J., Andrews, J.T., Lloyd, J.M., Moros, M., 2013a. An extensive and dynamic ice sheet on the West Greenland shelf during the last glacial cycle. Geology 41, 219–222.
Ó Cofaigh, C., Andrews, J.T., Jennings, A.E., Dowdeswell, J.A., Hogan, K.A., Kilfeather, A.A., Sheldon, C., 2013b. Glacimarine lithofacies, provenance and depositional processes on a West Greenland trough-mouth fan. J. Quat. Sci. 28, 13–26.
Ottesen, D., Dowdeswell, J.A., 2009. An inter-ice stream glaciated margin: submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard. Bull. Geol. Soc. Am. 121, 1647–1665.
Ottesen, D., Dowdeswell, J.A., Rise, L., 2005. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2500 km-long Norwegian-Svalbard margin (57°–80°N). Bull. Geol. Soc. Am. 117, 1033–1050.
Pfeffer, W.T., Harper, J.T., O'Neel, S., 2009. Kinematic constraints on glacier contributions to sea-level rise. Science 321, 1340–1343.
Powell, R.D., 1990. Glacimarine processes at grounding-line fans and their growth to ice-contact deltas. In: Dowdeswell, J.A., Scourse, J.D. (Eds.), Glacimarine Environments: Processes and Sediments, Geological Society, London, Special Publication, 53, pp. 53–73.
Rignot, E., Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland Ice Sheet. Science 311, 986–988.
Roberts, D.H., Rea, B.R., Lane, T.P., Schnabel, C., Rodés, A., 2013. New constraints on Greenland ice sheet dynamics during the last glacial cycle: evidence from the Uummannaq ice stream system. J. Geophys. Res.: Earth Surf. 118, 519–541. http://dx.doi.org/10.1002/jgrf20032.
Roksandic, M.M., 1979. Geology of the continental shelf off West Greenland between 61°15′N and 64°00′N: an interpretation of sparker seismic and echo sounder data. Grønlands Geologiske Undersøgelse 92, 15.
Sacchetti, F., Benetti, S., Ó Cofaigh, C., Georgiopoulou, A., 2012. Geophysical evidence of deep-keeled icebergs on the Rockall Bank, Northeast Atlantic Ocean. Geomorphology 159–160, 63–72.
Schumann, K., Völker, D., Weinrebe, W.R., 2012. Acoustic mapping of the Ilulissat Ice Fjord mouth, West Greenland. Quat. Sci. Rev. 40, 78–88.
Shepherd, A., et al., 2012. A reconciled estimate of ice-sheet mass balance. Science 338, 1183–1189.
Shipp, S.S., Anderson, J.B., Domack, E.W., 1999. Late Pleistocene–Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: part 1 – geophysical results. Geol. Soc. Am. Bull. 111, 1486–1516.
Shipp, S.S., Wellner, J.A., Anderson, J.B., 2002. Retreat signature of a polar ice stream: sub-glacial geomorphic features and sediments from the Ross Sea, Antarctica. In: Dowdeswell, J.A., Ó Cofaigh, C. (Eds.), Glacier-influenced Sedimentation on High-latitude Continental Margins, Geological Society, London, Special Publication, 203, pp. 277–304.
Syvitski, J.P.M., 1989. On the deposition of sediment within glacier-influenced fjords: oceanographic controls. Mar. Geol. 85, 301–329.
Syvitski, J.P.M., Burrell, D.C., Skei, J.M., 1987. Fjords: Processes and Products. Springer.
Syvitski, J.P.M., Stein, A.B., Andrews, J.T., Milliman, J.D., 2001. Icebergs and the sea floor of the East Greenland (Kangerlussuaq) continental margin. Arctic Antarctic Alpine Res. 33, 52–61.
Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J., Werner, F., 1998. The Norwegian-Greenland Sea continental margins: morphology and Late Quaternary sedimentary processes and environment. Quat. Sci. Rev. 17, 273–302.
Weidick, A., 1968. Observations on some Holocene glacier fluctuations in West Greenland. Meddeleser om Grønland 165 (6).
Weidick, A., Bennike, O., 2007. Quaternary glaciation history and glaciology of Jakobshavns Isbræ and the Disko Bugt region, West Greenland: a review. Geol. Surv. Den. Green. Bull. 14, 1–78.
Wellner, J.S., Lowe, A.L., Shipp, S.S., Anderson, J.B., 2001. Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: implications for ice behaviour. J. Glaciol. 47, 397–411.
Winkelmann, D., Jokat, W., Jensen, L., Schenke, H.W., 2010. Submarine end moraines on the continental shelf off NE Greenland – implications for Lateglacial dynamics. Quat. Sci. Rev. 29, 1069–1077.
Woodworth-Lynas, C.M.T., Josenhans, H.W., Barrie, J.V., Lewis, C.F.M., Parrott, D.R., 1991. The physical processes of seabed disturbance during iceberg grounding and scouring. Cont. Shelf Res. 11, 939–951.